THE GREAT COURSES®

Topic
Science
& Mathematics

Subtopic
Earth Science

Earth's Changing Climate

Course Guidebook

Professor Richard Wolfson
Middlebury College

PUBLISHED BY:

THE GREAT COURSES
Corporate Headquarters
4840 Westfields Boulevard, Suite 500
Chantilly, Virginia 20151-2299
Phone: 1-800-832-2412
Fax: 703-378-3819
www.thegreatcourses.com

Copyright © The Teaching Company, 2007

Printed in the United States of America

This book is in copyright. All rights reserved.

Without limiting the rights under copyright reserved above,
no part of this publication may be reproduced, stored in
or introduced into a retrieval system, or transmitted,
in any form, or by any means
(electronic, mechanical, photocopying, recording, or otherwise),
without the prior written permission of
The Teaching Company.

Richard Wolfson, Ph.D.

Professor of Physics and Environmental Studies, Middlebury College

Richard Wolfson is the Benjamin F. Wissler Professor of Physics at Middlebury College. He did his undergraduate work at MIT and Swarthmore College, graduating from Swarthmore with a double major in physics and philosophy. He holds a master's degree in environmental studies from the University of Michigan and a Ph.D. in physics from Dartmouth. Dr. Wolfson's published work encompasses such diverse fields as medical physics, plasma physics, solar energy engineering, electronic circuit design, observational astronomy, theoretical astrophysics, nuclear issues, and climate change. His current research involves the eruptive behavior of the Sun's outer atmosphere, or corona, as well as terrestrial climate change and the Sun-Earth connection.

Professor Wolfson is particularly interested in making science relevant to nonscientists and to students from all walks of academic life. His textbook, *Physics for Scientists and Engineers* (Addison Wesley, 1999), saw three editions and has been translated into several languages; it was followed by *Essential University Physics* (Addison Wesley, 2006). Dr. Wolfson's books *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (MIT Press, 1993) and *Simply Einstein: Relativity Demystified* (W.W. Norton, 2003) exemplify his interest in making science understandable to nonscientists. His latest book, *Energy, Environment, and Climate* (W.W. Norton, 2007), is an undergraduate textbook accessible to general readers. He has also published in *Scientific American* and writes for *World Book Encyclopedia*. His previous courses for The Teaching Company include *Einstein's Relativity and the Quantum Revolution: Modern Physics for Nonscientists* (1999) and *Physics in Your Life* (2004). Dr. Wolfson has spent sabbaticals at the National Center for Atmospheric Research in Boulder, Colorado; at St. Andrews University in Scotland; and at Stanford University.

Table of Contents
Earth's Changing Climate

Professor Biography i
Course Scope 1
Lecture One Is Earth Warming? 3
Lecture Two Butterflies, Glaciers, and Hurricanes 7
Lecture Three Ice Ages and Beyond 10
Lecture Four In the Greenhouse 13
Lecture Five A Tale of Three Planets 17
Lecture Six Global Recycling 21
Lecture Seven The Human Factor 26
Lecture Eight Computing the Future 31
Lecture Nine Impacts of Climate Change 36
Lecture Ten Energy and Climate 42
Lecture Eleven Energy—Resources and Alternatives 47
Lecture Twelve Sustainable Futures? 53
Figures 58
Data Sources for Figures 71
Glossary 74
Bibliography 79

Earth’s Changing Climate

Scope:

Is Earth warming? Yes: Recent years have been the warmest our planet has experienced in the past millennium and quite possibly for 100,000 years or more. Are we humans responsible? At least in part: We’ve increased the concentration of heat-trapping gases in Earth’s atmosphere to levels not seen in the past million years and probably much longer. What does the future hold? A continued warming trend, increased melting of polar and glacial ice, rising sea level, altered weather patterns, and more intense precipitation and storms. What will be the impact? That’s less certain—but it will surely include changes in agriculture, flooding of low-lying areas, extinction of species, and economic consequences. Sudden, large-scale disruptions of Earth’s climate are less likely but lurk as increasing possibilities beyond the current century.

How do we know that Earth’s climate is changing? How can we project future climate change? Why do we attribute climate change to human activities? This course explores the solid science behind climate change, the myriad evidence pointing to ongoing global warming, and the modeling techniques used to project future climate. The course assumes no background in science and is designed to give students a firm understanding of the scientific issues that underlie climate change—issues that must ultimately guide public policy in the coming decades.

This is a course about the science of climate change. It is not an advocacy program. Other groups and individuals, through writings, films, and public information campaigns, attempt to educate and, simultaneously, to influence public behavior. This course seeks only to educate. As such, it presents evidence for what has become an overwhelming scientific consensus on global climate change and its causes. You should come away from the course better equipped to make your own judgments about the appropriate public policies to cope with climate change, but this course won’t make those judgments for you. That said, the course at its end acknowledges the need for action on climate change—but it suggests a range of alternatives rather than dictating one course of action.

The course is presented in 12 lectures. The first half explores our scientific understanding of climate, while the second half deals with future climates and the human role in climate change. The first lecture, “Is Earth

Warming?” gives an introduction to the entire course, distinguishes clearly between science and policy issues, and presents evidence for recent planetary warming in the context of the 150-year record of measured global temperatures. The second lecture, “Butterflies, Glaciers, and Hurricanes,” examines a host of phenomena—from species migrations to ice melt to storm intensities—that, along with rising temperature, point to ongoing climate change. Lecture Three, “Ice Ages and Beyond,” looks at ancient climates, inferred from a wide range of physical, chemical, and biological indicators. Lectures Four and Five, “In the Greenhouse” and “A Tale of Three Planets,” explore the scientific principles that establish climate and show how the climates of our neighbor planets Venus and Mars confirm our understanding of Earth’s climate. These lectures also include a brief discussion of the nature of scientific theories and of certainty and uncertainty in science. The first half of the course ends with “Global Recycling,” a look at the complex cycling of materials—especially carbon—in the atmosphere, oceans, soils, and biological systems.

Lecture Seven, “The Human Factor,” confronts the evidence that the climate change of recent decades is predominantly the result of human activities—largely but not exclusively the combustion of fossil fuels. Lecture Eight, “Computing the Future,” shows how computer models combine basic scientific principles with complex feedback effects and observations of past climates to project scenarios for future climate change; the lecture also presents test results that give us confidence in computer climate models. The ninth lecture, “Impacts of Climate Change,” explores expected changes in weather patterns, heat waves, sea level, ice sheets, drought, and other effects of a changing climate. Lecture Ten, “Energy and Climate,” takes a realistic look at the relatively few basic alternatives we have to climate-altering fossil energy sources. “Energy—Resources and Alternatives” follows with a more detailed look at the prospects for alternative energy technologies and their role in mitigating climate change. The course ends with Lecture Twelve, “Sustainable Futures?”

Lecture One

Is Earth Warming?

Scope: Earth's climate is changing. Recent decades have seen a steep rise in global temperatures. Thermometer-based temperature records show a pattern of temperature variation that spans 150 years, from the mid-19th century to the present. What does this pattern tell us? How do we take our planet's temperature? This lecture explores these scientific questions and shows how climate scientists arrive at values for global temperatures.

Questions about climate change and its causes are squarely in the realm of science. Questions of what to do about climate change are in the realm of public policy. With climate change, issues of science, policy, and political opinion often become muddled. This course is about science, and what's presented here is based on solid scientific evidence developed through the course of research, peer-reviewed publication, and the emergence of scientific consensus. Science can help guide policy, but science alone can't dictate the best policy decisions. This first lecture includes an introduction to the course that clearly distinguishes the realms of science and policy.

Outline

I. This course deals with *climate*, not *weather*. *Climate* refers to long-term trends; *weather*, to short-term variations in atmospheric conditions. We jump right in with a look at Earth's average temperature over the past 150 years.

- **A.** There will be lots of graphs in this course! My obligation is to explain clearly what each graph shows, what the axes are, what units are used, where the data come from, and what the uncertainties are.
- **B.** We begin by looking at global average temperatures since 1860, expressed as deviations from the 1961–1990 average temperature. See Figure 1.
  - **1.** Temperatures are in degrees Celsius, used almost universally in science; 1 degree Celsius is 1.8 degrees Fahrenheit.

    2. It is easier to measure temperature changes accurately than to measure temperature itself; thus, climate trends are often shown as deviations.
    3. Data are from thermometers; more on this shortly.
    4. Temperature deviations in the early decades are good to about ±0.2°C; by 1950, this uncertainty in the global temperature record drops to roughly ±0.05°C.

C. The 150-year temperature record shows a lot of variation but can be divided into several major sections:

    1. A roughly constant average temperature in the late 19th century.
    2. A rise in the early 20th century.
    3. A leveling off or slight decline in the mid-20th century.
    4. A steep rise in the final decades of the 20th century, continuing into the 21st century.

D. What causes this pattern of temperature variation, and how typical is it for our planet? That's a major theme of this course, but here's a quick summary:

    1. Variations in the early part of the 150-year temperature record are largely explainable by natural variations within the climate system, by volcanic eruptions, and by variations in the Sun's energy output.
    2. Variations in recent decades are largely the result of human activities, predominantly but not exclusively the burning of fossil fuels. The second half of the course will detail the evidence for a human impact on Earth's climate.

E. So far, we've discussed only the global average temperature. Regional temperatures show considerably greater variability, and land temperatures have risen more than ocean temperatures. The temperature increase has also been greater at high latitudes. (Take another look at Figure 1, which also shows Northern Hemisphere land temperatures.)

F. The bottom line is that Earth's average temperature has risen about 0.65°C since the start of the 20th century, with nearly all regions of the globe experiencing a temperature increase. This may not seem like much, but we'll see in subsequent lectures why even such a small rise in the global average temperature is climatologically significant.

II. How do we take Earth's temperature?

- **A.** A single thermometer won't do! But since the mid-19th century, there have been enough data available from thermometer-based measurements to compute an average global temperature at Earth's surface. Data sources include:
    - **1.** Air temperatures from land-based weather stations (surface air temperature, or SAT), with thermometers usually placed 1–2 meters above the surface.
    - **2.** Marine air temperature (MAT), taken just above the sea surface from ships and buoys.
    - **3.** Sea-surface water temperature (SST), taken from ships.
- **B.** All these measurements require corrections to ensure accurate global averages:
    - **1.** Corrections for instrumentation and placement.
    - **2.** Corrections for water-temperature sampling.
    - **3.** Corrections for the *urban heat island effect*.

III. Now let's turn to a discussion of science, policy, and this course.

- **A.** Science deals with the facts and governing principles of physical reality. Science is never 100% certain, but neither is anything else. Science develops through observation, experimentation, theorizing, and publication in open, peer-reviewed literature. Scientific consensus emerges when the results of observation and experiments overwhelmingly support a given idea or hypothesis. Science can be quite certain of "big picture" ideas without being certain of every detail. Such is the case with the state of climate science today.
- **B.** Public policy involves society's decisions about what to do in the face of many factors—including the findings of science. Science can guide policy by providing factual information and projections of future conditions, but science alone can't determine the right policy decisions.
- **C.** Ongoing changes in Earth's climate have significant implications for public policy. This situation has led to a muddling of science and policy questions in the minds of the public and of many policymakers. This course is about climate science, not politics or policy debates.

D. The two halves of this course deal with:
   1. Our basic scientific understanding of Earth's climate system, including a look at past climates and the principles that determine climate.
   2. Our evidence for a human impact on climate, our understanding of the causes of that impact, and the implications for future climate and for human use of energy.

Suggested Reading:

Houghton, chapter 1.

Wolfson, chapter 14, section 14.1 (skip "Going Further Back").

Going Deeper:

Harvey, chapter 5.

Intergovernmental Panel on Climate Change (IPCC) 4, chapter 3, section 2.

Web Sites to Visit:

Climatic Research Unit, University of East Anglia. Probably the most authoritative source for the instrumental temperature record discussed in this lecture. http://www.cru.uea.ac.uk/.

Questions to Consider:

1. Can you tell if the 150-year global temperature record discussed in this lecture represents anything unusual in the history of Earth's climate? If not, what additional information would you need to decide whether or not recent climate change is unusual?
2. Describe two of the difficulties in arriving at an accurate value for the global average temperature and tell how scientists correct for these difficulties.

Lecture Two

Butterflies, Glaciers, and Hurricanes

Scope: Rising thermometers aren't the only indicators of climate change. Other evidence points to increasing temperatures, as well as more subtle effects associated with changing climate. Hundreds of species show shifts in range consistent with a warming climate. Mountain glaciers and polar ice are melting, often at accelerating rates. Weather patterns are changing, with more intense precipitation events occurring, a narrowing of the day-night temperature difference, and increases in hurricane intensity. However, a variety of factors besides climate can influence biological, glaciological, and meteorological phenomena, and even different climate-related effects can work in opposite directions. This lecture also looks at these more subtle points and shows how statistical analysis nevertheless yields patterns that show clear "fingerprints" of climate change in a host of natural systems.

Outline

I. Surface temperatures aren't the only indications that Earth is warming.

- **A.** Boreholes provide a record of surface temperatures in the recent past, because the surface temperature "signal" propagates into the ground. Borehole temperatures smooth out the year-to-year fluctuations and provide a general trend consistent with surface temperatures.
- **B.** The heat content of the upper layers of the ocean shows an overall increase over the past few decades.
- **C.** Temperatures in the lower atmosphere (the *troposphere*), although harder to measure than surface temperatures, show an increase consistent with the rising surface temperatures.
- **D.** Temperatures in the upper atmosphere (the *stratosphere*) show a decrease. As Lectures Four and Five will show, this is consistent with increasing surface temperatures.

II. Earth's *cryosphere*—ice and snow cover—responds to changing temperature. Because it takes a lot of energy to melt snow and ice, these changes are relatively slow and reflect the overall temperature trends.

- **A.** Most mountain glaciers around the world are shrinking at accelerating rates. Glacier growth and shrinkage are determined by a balance between accumulating snow and the effects of melting.
- **B.** Arctic sea ice is melting at accelerating rates. Melting sea ice results in a *positive feedback*, as darker ocean water absorbs more sunlight and results in further warming. See Figure 2.
- **C.** Land-based ice caps are also melting.
  - **1.** Greenland's ice melt is especially significant and is accelerating rapidly.
  - **2.** The situation in Antarctica is less clear, with melting at the margins and some ice cap growth in the interior.
  - **3.** A concern is that meltwater flowing under the ice may lubricate ice sheets, making them prone to slide into the sea.

III. Tracking weather patterns over decades shows changes that would be expected with a changing climate.

- **A.** There are more extremely hot days and heat waves.
- **B.** Precipitation is increasing as warmer temperatures drive more evaporation.
  - **1.** The change is not uniform, with some parts of the world drying and others becoming wetter.
  - **2.** More precipitation is falling in intense, brief events.
- **C.** The *diurnal temperature range* is decreasing, as night temperatures rise faster than daytime temperatures.
- **D.** Hurricane intensity is increasing, especially in the North Atlantic. See Figure 3.
  - **1.** Evidence for an increase in the number of hurricanes is elusive.
  - **2.** Changes in hurricane intensity seem to correlate with rising sea-surface temperature.

IV. Plant and animal species show changes in geographical range and in timing of behaviors.

- **A.** Northern hemisphere species are moving northward and upward.
- **B.** Springtime events are occurring earlier.

C. Although these changes have complex causes, 87% are in the direction consistent with increasing temperature.

Suggested Reading:

Houghton, chapter 4, pp. 56–64.

Wolfson, chapter 14, section 14.2 to “Going Further Back.”

Going Deeper:

Parmesan and Yohe.

Web Sites to Visit:

National Snow and Ice Data Center. Images and data showing changing conditions in Earth’s cryosphere. http://nsidc.org/.

World Glacier Monitoring Service. This Swiss site carries yearly data on hundreds of glaciers worldwide. http://www.geo.unizh.ch/wgms/.

Questions to Consider:

1. Why might increased precipitation and cloudiness be expected consequences of a global temperature increase?
2. What are other factors besides climate change that might affect species ranges and account for the fact that most but not all species show changes consistent with increasing temperature?

Lecture Three
Ice Ages and Beyond

Scope: Thermometer-based temperature records go back only 150 years. This lecture explores the techniques scientists use to push global temperatures back thousands, millions, and even billions of years. In particular, we'll explore the cyclic pattern of ice ages punctuated by brief warmer spells. Our understanding of this pattern involves a complex interaction among astronomical effects on Earth's orbit and axis, along with feedback effects that drive changes in the levels of atmospheric carbon dioxide and other gases. The picture of past climates developed in this lecture will be important in the next few lectures, where we seek to understand the scientific principles that establish climate, and in later lectures, where we show why recent climate change is largely attributable to human activities.

Outline

I. Are the patterns of variation seen in the 150-year instrumental temperature record typical of natural variations in Earth's climate? Or is there something unusual about recent temperature increases, especially in the past few decades? Answering these questions requires pushing the temperature record back in time.

- **A.** Because there aren't enough accurate temperature-based measurements to calculate a global average temperature before the mid-19th century, scientists use *proxies*, physical quantities that serve as indicators of temperature. Commonly used temperature proxies include:
  - **1.** Annual tree rings, whose thickness and wood density varies with temperature and length of growing season. Tree rings are most valuable in regions showing large winter-summer temperature variations.
  - **2.** Coral reefs, which form annual layers of calcium carbonate whose analysis yields information about the temperature at the time of formation. Corals are most useful for tropical ocean temperatures.

    3. Lake sediments, the thickness of which indicates the rate of snowmelt that feeds streams carrying sediment and, thus, provides a measure of springtime temperatures. Further, the pollen content of lake sediments tells us about plant species, giving a general indication of climatic conditions.
    4. Isotope ratios from ice cores and shell-forming marine organisms also provide a measure of temperature, specifically, ratios of the two stable isotopes oxygen-16 and oxygen-18; a similar technique uses hydrogen isotopes.

  B. A number of independent multiproxy studies use statistical methods to combine different proxy temperatures to reconstruct global or hemispherical temperature patterns back one or two millennia. See Figure 4.

    1. The temperature reconstructions vary somewhat, but all show patterns of gradually declining temperature over most of the past millennium, followed by a sharp upturn through the 20th century and into the 21st century.
    2. These reconstructions suggest that Earth's current climate is the warmest in at least the past millennium.
    3. An independent study by the U.S. National Academy of Sciences affirms these findings, with considerable confidence in the reconstruction of the past 400 years and more uncertainty for earlier years.

  C. Ice cores from Greenland and Antarctica use oxygen and hydrogen isotope ratios to provide temperatures ranging back nearly 1 million years.

    1. These records show a cyclic pattern of brief (10,000- to 20,000-year) warm spells called *interglacials*, separated by longer cold spells (*ice ages*). For the past half million years, this cycle has repeated on roughly 100,000-year intervals. See Figures 5 and 6.
    2. This pattern results from subtle changes in Earth's orbit and tilt, along with complex feedback effects in the climate system.

II. Climate reconstructions going back still further use a variety of proxies, including geological evidence for ice, fossil vegetation, and oxygen isotope ratios from fossil plankton.

A. This evidence suggests that Earth has been considerably warmer in times past, especially during the age of the dinosaurs, hundreds of millions to tens of millions of years ago.

B. There is also evidence of as many as four *snowball Earth* phases, when the planet may have frozen solid. These occurred between 750 and 580 million years ago and were followed by rapid thawing associated with changes in the atmosphere due to gaseous emissions from volcanoes.

Suggested Reading:

Houghton, chapter 4, pp. 64 to end of chapter, emphasizing temperature.

Wolfson, chapter 14, "Going Further Back" to end of chapter.

Going Deeper:

Harvey, chapter 1.

IPCC 4, chapter 6.

Ruddiman, chapters 7–10.

Web Sites to Visit:

Carbon Dioxide Information Analysis Center (CDIAC). At this particular CDIAC page, you'll find graphs and data on global and regional temperatures from sites around the world, going back hundreds of thousands of years. http://cdiac.ornl.gov/trends/temp/contents.htm.

Questions to Consider:

1. Distinguish between an instrumental temperature record and a proxy reconstruction.
2. What is the approximate temperature difference between interglacial warm periods, such as we enjoy today, and the ice ages? Express in both Celsius and Fahrenheit.
3. What is the ultimate cause of the cyclic pattern, seen for the past half-million years, whereby ice ages alternate with briefer warm spells?

Lecture Four
In the Greenhouse

Scope: What determines a planet's temperature and, thus, establishes its overall climate? Ultimately, stable climate results from a balance between incoming solar energy and heat that a planet radiates to space. Well-established fundamental principles of physics govern that balance. But a planetary atmosphere complicates the picture, absorbing outgoing energy and, thereby, altering the energy balance. The result is the greenhouse effect, which can keep a planet significantly warmer than it would otherwise be. For Earth, the naturally occurring greenhouse effect—mostly the result of atmospheric water vapor and, to a lesser extent, carbon dioxide—warms our planet by nearly 60°F (33°C) over what it would be absent these gases. Changes in atmospheric composition will alter the quantitative value of this greenhouse effect, and that's the primary reason for concern about human-caused climate change.

Outline

I. *Energy balance* is the key to a stable climate—or a stable temperature in any system, be it a house, a planet, a star, or a pan on a stove.

- **A.** A greenhouse provides a good example, maintaining a balance between heat loss and incoming sunlight.
- **B.** A planet works the same way, balancing energy from the Sun (or another star) with infrared energy radiated to space.
  1. We know the rate at which sunlight delivers energy: This averages about 240 watts for every square meter of Earth's surface.
  2. We know the law that governs radiation: The energy loss by radiation is proportional to the fourth power of the temperature.
  3. Equating energy gain and loss gives an average temperature of about –18°C or 0°F.
  4. This is in the right ballpark, but it seems a bit cool for a global average. What's wrong with the calculation?

II. We've neglected Earth's atmosphere, which warms the planet's surface through the *greenhouse effect*.

- **A.** The gases that make up most of the atmosphere—roughly 80% nitrogen and 20% oxygen—are largely transparent both to incoming sunlight and to outgoing infrared.
- **B.** Other gases, especially water vapor and carbon dioxide, are transparent to sunlight but considerably opaque to infrared.
  - **1.** These are called *greenhouse gases* (GHGs). The name is somewhat of a misnomer, because the glass in a greenhouse blocks predominantly the bulk motion of heated air out of the greenhouse, not infrared radiation.
  - **2.** Greenhouse gases tend to have more complicated molecules than nitrogen and oxygen, and that's the fundamental reason for their greater absorption of infrared.
  - **3.** The atmospheric greenhouse gases absorb outgoing infrared radiation, and as a result, Earth's surface warms until it reaches energy balance at a higher temperature than it would have without the greenhouse gases.
  - **4.** The *natural greenhouse effect*, due largely to naturally occurring water vapor but also to naturally occurring carbon dioxide, raises the surface temperature by about 33°C or 60°F. That makes Earth a much more comfortable place for living things.
- **C.** Three ways to understand the greenhouse effect involve increasing levels of scientific sophistication.
  - **1.** Simple: Greenhouse gases act as an insulating "blanket," making it harder for energy to escape and resulting in the warming of the surface until its higher temperature can still force enough energy through to maintain energy balance.
  - **2.** More sophisticated: Greenhouse gases absorb outgoing infrared and heat up. They re-radiate their energy both upward to space and downward to the surface. The surface is warmed by this *back radiation* and, therefore, radiates more infrared to maintain energy balance.
  - **3.** Most sophisticated: The upper atmosphere, being cooler than Earth's surface, can't emit as much radiation as the surface. Radiation from the atmosphere alone, then, can't keep the planet in energy balance. Therefore, the surface temperature

must be higher than the atmosphere temperature to provide enough additional radiation that can escape through the nearly but not completely opaque greenhouse gases. Thus, the greenhouse effect depends crucially on the *temperature difference* between surface and upper atmosphere. Increasing greenhouse warming actually entails *cooling* the upper atmosphere.

III. Earth's actual energy balance is more complex still. Other factors include the following. See Figure 7.

A. Reflection, which returns incoming sunlight to space before it can participate in energy flows that establish surface and atmospheric temperatures.

1. Reflection occurs from clouds, from ice and snow, from particles suspended in the atmosphere (aerosols), and from deserts and other light-colored surfaces.

2. Changes in the amount of sunlight reflected will change Earth's energy balance.

B. Convection, evaporation, and transpiration, which carry energy from the surface into the atmosphere by the bulk motion of heated air and moisture. These processes are affected by surface temperature, vegetation, and other factors.

Suggested Reading:

Houghton, chapter 2.

Going Deeper:

Harvey, chapter 2 through section 2.3.

Ruddiman, chapter 2.

Wolfson, chapter 12.

Web Sites to Visit:

Hadley Centre of the British Meteorological Office. The highly respected British Met (for Meteorological) Office provides a thorough introduction to the greenhouse effect at this page on its Web site. http://www.metoffice.gov.uk; search for brochures.

Questions to Consider:

1. Give explanations of the greenhouse effect at two different levels of scientific sophistication.
2. What is meant by the statement “the natural greenhouse effect amounts to 33°C”? Why is the effect associated with a number?
3. Name two greenhouse gases. Which makes the greatest contribution to the *natural* greenhouse effect?

Lecture Five

A Tale of Three Planets

Scope: We can't do controlled experiments to verify the theory of the greenhouse effect. However, we can look at past climates to see how temperatures and greenhouse gases are correlated. Also, nature provides us with an "experiment" in the three planets Venus, Earth, and Mars. Mars's atmosphere is so thin that it has almost no greenhouse effect. Venus's dense atmosphere results in a runaway greenhouse effect that increases the planet's temperature by hundreds of degrees. Earth lies in between, with its 33°C greenhouse effect.

But isn't this still "just a theory"? It is—but in science, *theory* doesn't mean hypothesis or speculation. It means a coherent body of scientific understanding, with a conceptual framework supported by diverse evidence. The theory of the greenhouse effect is one such body of understanding. That doesn't mean we understand every detail of Earth's climate, but it does mean that our basic understanding is grounded in solid scientific principles.

Outline

I. How do we know that greenhouse gases are associated with the warming of Earth's surface? One way is to look at past climates and their relation to greenhouse-gas concentrations.

A. Although water vapor is the dominant greenhouse gas for Earth's natural greenhouse effect, carbon dioxide (CO_2) plays a more important role in varying the strength of the greenhouse effect.

1. That's because water-vapor concentration adjusts nearly instantaneously to changing conditions, while added CO_2 remains in the atmosphere for a long time (more on this in Lecture Six).

2. The same ice cores that provide a record of past temperatures also give scientists a record of atmospheric composition. These data come from analysis of ancient air bubbles trapped in the ice. For so-called *trace gases*—those other than nitrogen and oxygen—concentrations are measured in parts per million (ppm) or parts per billion (ppb) by volume.

    3. Temperature and CO_2 concentration show a remarkable correlation. See Figure 8.

  B. There's not a simple cause-and-effect relation here. Rather, subtle changes in Earth's orbital parameters result in a slight warming; that, in turn, causes CO_2 release to the atmosphere. More CO_2 means more greenhouse warming and more CO_2 release. The temperature "leapfrogs" upward through such *feedback mechanisms*.

  C. A similar relation between temperature and CO_2 concentration holds farther back. During the age of dinosaurs, around 100 million years ago, warm-climate organisms thrived even in polar regions. CO_2 levels at this time probably exceeded 1000 ppm. Geologic processes—plate tectonics, volcanism, and rock weathering—are the major causes of climate change on these long time scales.

II. Nature also provides us with a climate "experiment" in the form of our neighbor planets Venus and Mars.

  A. A simple calculation based on energy balance with no atmosphere yields average temperatures of:

    1. –50°C for Mars.
    2. –18°C for Earth (as described in Lecture Four).
    3. 55°C for Venus.

  B. Actual surface temperatures are about the same for Mars (–63 K), a bit warmer for Earth (15°C), and a lot warmer for Venus (about 500°C—hot enough to melt lead). Why the discrepancies?

    1. Earth's 33°C difference is due to the greenhouse effect, as described in the preceding lecture.
    2. Mars's atmosphere has only about 1% the density of Earth's, so it has a negligible greenhouse effect. It's actually cooler because of reflection of sunlight.
    3. Venus's atmosphere has 100 times the density of Earth's, and it's about 96% carbon dioxide. Although Venus's proximity to the Sun would make it only modestly warmer than Earth, that was enough to evaporate Venus's surface water, resulting in a

“runaway” greenhouse effect powered at first by water vapor and later maintained by carbon dioxide.

C. Our neighbor planets confirm the theory of the greenhouse effect: that greenhouse gases warm a planet’s surface beyond the temperature that would result from energy balance in the absence of those gases.

D. Earth appears safe from a Venus-like runaway greenhouse effect, but Earth is still subject to warming if the concentration of greenhouse gases increases.

III. Isn’t this all “just a theory” that might or might not prove correct?

A. “Just a theory” is a misleading phrase. In science, a theory is a set of coherent principles that explain a broad range of physical phenomena. A theory gains credibility when it’s supported by evidence from observations and laboratory experiments, and it’s rejected when physical reality presents evidence that contradicts the theory. Established theories have survived that test. Some examples of well-established scientific theories include:

1. The theory of relativity in physics, which describes phenomena ranging from the overall structure of the Universe, to numerous astrophysical events, to the functioning of the global positioning system.
2. The theory of evolution in biology, which describes the origin of species through the evolutionary process.
3. The theory of plate tectonics in geology, which describes the movement of the continents over geologic time.
4. The theory of the greenhouse effect, which describes the fundamental principles that establish planetary climates.

B. A theory need not have explanations for every detail in order to qualify as being a solidly established body of scientific knowledge. Although evolution doesn’t yet describe every step in the origin of every species, that doesn’t invalidate the theory of evolution. Although relativity can’t tell us everything that goes on inside a black hole, that doesn’t invalidate the theory of relativity. And although climate scientists don’t understand every detail of Earth’s complex climate system, that doesn’t invalidate the theory of the greenhouse effect.

Suggested Reading:

Houghton, chapter 4, p. 66 onward, emphasizing CO_2-temperature connection.

Wolfson, chapter 12, section 5.

Going Deeper:

Ruddiman, chapters 4 and 8.

Schneider, Rosencranz, and Niles, chapter 1, especially p. 42 onward.

Web Sites to Visit:

Carbon Dioxide Information Analysis Center. At this particular CDIAC page, you'll find graphs and data on atmospheric carbon dioxide from sites around the world and on time scales ranging from decades to hundreds of thousands of years. http://cdiac.ornl.gov/trends/co2/contents.htm.

Questions to Consider:

1. Graphs of temperature and carbon dioxide concentration over the past 160,000 years show a remarkable correlation. Why can't we draw the simple conclusion that the warm periods result from an increase in carbon dioxide, leading to an increase in temperature?
2. Venus receives only twice as much energy from the Sun as does Earth, and most of that is reflected back into space. Yet Venus is much hotter than Earth. Why?
3. What's a scientific theory? How is it more than just a hypothesis or guess?

Lecture Six

Global Recycling

Scope: The water vapor and carbon dioxide that create Earth's greenhouse effect don't remain in the atmosphere forever. They cycle through the atmosphere, oceans, soil and rocks, and living things. A typical water molecule remains in the atmosphere about a week; a carbon dioxide molecule, about five years. Plants remove carbon dioxide from the atmosphere and produce energy-storing foods through photosynthesis. Plants and animals use this energy, taking in oxygen and returning carbon dioxide to the atmosphere. There's also carbon exchange between atmosphere and oceans. And a tiny fraction of the carbon gets stored as fossil fuels. Carbon dioxide emissions from human combustion of fossil fuels constitute a small fraction of the global carbon cycle—but that carbon accumulates in the system, pushing up the atmospheric concentration. It will take centuries to millennia for this extra anthropogenic carbon to leave the system.

Outline

I. With respect to matter, Earth is essentially a closed system. The materials that make up the planet and its atmosphere and oceans never disappear, but some cycle continually among different parts of the Earth system.

A. This contrasts with energy. With respect to energy, Earth isn't closed; energy arrives as sunlight and returns to space as infrared radiation. The preceding lectures described this energy flow, and Lecture Ten will explore it further.

B. Many material cycles are important to climate, including the water cycle and the carbon, nitrogen, phosphorus, and sulfur cycles. But of these, water and carbon are the most important, in part because both water vapor and carbon dioxide are significant greenhouse gases.

II. The *water cycle*, or *hydrologic cycle*, involves the evaporation of surface water and its subsequent precipitation onto land and oceans.

- **A.** Solar energy ultimately drives the water cycle, with the rate of evaporation strongly dependent on temperature.
- **B.** The amount of water in the atmosphere is tiny compared with the amount stored in the oceans and cryosphere (frozen water). Although it varies with time and location, water vapor typically constitutes a few percent of the lower atmosphere.
- **C.** Atmospheric water vapor responds quickly to changing temperature and other conditions.
  - **1.** A typical water molecule remains in the atmosphere for only about a week before it's removed by precipitation.
  - **2.** From the long-term perspective of climate, therefore, atmospheric water vapor can be considered to adjust almost instantaneously to changing surface conditions.
  - **3.** Atmospheric water vapor contains the energy—called *latent heat*—that was required to evaporate it. Therefore, the water cycle also contributes to the flow of energy from surface to atmosphere, as discussed in Lecture Four.

III. The *carbon cycle* operates on many time scales and involves interactions among atmosphere, land, oceans, biological systems, and on the longest time scales, geological processes. See Figure 9.

- **A.** Let's first define the terms *tons*, *tonnes*, and *gigatonnes*.
  - **1.** In the United States, 1 ton is 2000 pounds. In the rest of the world, 1 ton means 1 *metric ton*, usually spelled *tonne*. One tonne is 1000 kilograms, or 2200 pounds. Thus, a U.S. ton and a metric ton are about the same. Numbers given here are in metric tons, but the difference isn't significant.
  - **2.** The metric system uses prefixes for powers of 10, such as kilometer (km) for 1000 meters and kilogram (kg) for 1000 grams. The prefix *giga* (G) stands for billion; thus, 1 *gigatonne* (Gt) is a billion tonnes. That's the unit used for global carbon flows. A gigatonne is the same as a *petagram* (1000 trillion grams, or 10^{15} grams).
- **B.** The most rapid part of the carbon cycle involves carbon exchanges between air and water, air and living things, and air and soil.
  - **1.** Atmospheric carbon dioxide dissolves in water, a process that removes CO_2 from the air. But dissolved CO_2 also escapes to the atmosphere. Normally, these two processes are nearly in

balance, and the flows each way amount to about 90 Gt of carbon (measured as C, not CO_2) per year. Because warmer water holds less CO_2, warming of the ocean surface sends more CO_2 into the atmosphere.

2. Plants take CO_2 from the atmosphere through *photosynthesis*, using solar energy to form carbohydrates that are the fuels for living things. Photosynthesis removes about 110 Gt of carbon from the atmosphere each year. In the process, plants release oxygen to the atmosphere.
3. Plants and animals use the energy stored in carbohydrates for cellular activities and locomotion. This process of *respiration* takes oxygen from the atmosphere and returns CO_2. Respiration, along with the decay of dead and waste matter, returns nearly all of the 110 Gt of CO_2 that was removed in photosynthesis. Rivers carry some additional carbon into the oceans.
4. The atmosphere, living things, soils, and surface ocean waters all represent short-term carbon *reservoirs*. Cycling among these reservoirs occurs mostly on relatively short time scales. In particular, a typical carbon dioxide molecule remains in the atmosphere only about five years.
5. But the rapid cycling of carbon through the atmosphere–biosphere–surface ocean system means that any carbon added to that system remains there much longer—for hundreds to thousands of years. Because the added carbon cycles through the atmosphere, the level of atmospheric carbon dioxide goes up and stays up for a long time.

C. Two processes are involved in the long-term removal of carbon from the rapidly cycling atmosphere–biosphere–surface ocean system.

1. Marine organisms die and sink into the deep ocean, taking their carbon with them. This is the *biological pump*.
2. Upwelling of deep water and upward diffusion of carbon nearly balance the biological pump.
3. The result is a net downward flow of carbon of only about 2 Gt per year. That's why it takes hundreds to thousands of years to remove excess carbon from the system.
4. This carbon joins the huge (39,000-Gt) reservoir of carbon stored in the deep ocean.

        5. Carbon slowly leaves the deep ocean reservoir and is incorporated into ocean sediments, which eventually form rocks.
    - **D.** Two additional processes operate on very long time scales of tens to hundreds of millions of years.
        1. Geological processes eventually recycle buried carbon through volcanism.
        2. A tiny fraction of carbon fixed by photosynthesis is buried before it has a chance to decay. Over millions of years, this becomes the fossil fuels coal, oil, and natural gas. We're burning those fuels now, adding CO_2 to the atmosphere.

- **IV.** Let's briefly review the first half of the course.
    - **A.** Earth is warming, with especially rapid warming evident in recent decades of the 150-year thermometric temperature record.
    - **B.** A host of other evidence corroborates the thermometric record.
    - **C.** Using proxy indicators pushes the climate record back further in time.
        1. Studies suggest that the warming of the late 20th and early 21st centuries is unprecedented in the past 1000 years.
        2. Ice-core records show a pattern of cold ice ages punctuated by shorter, warmer interglacial spells lasting a few tens of thousands of years. For the past half million years, this pattern has repeated on a roughly 100,000-year time scale.
    - **D.** We understand the fundamental processes that establish planetary climates based on solid physical principles.
        1. Stable climate entails a balance between incoming sunlight and outgoing infrared radiation.
        2. Infrared-absorbing greenhouse gases in a planet's atmosphere alter the details of this balance, causing the planet's surface to warm. For Earth, the most important greenhouse gases are water vapor and carbon dioxide. Together, they provide a natural greenhouse warming of about 33°C or 60°F.
        3. Ice-core data show that atmospheric carbon dioxide and temperature have been closely correlated for nearly a million years, and less direct evidence suggests that such a correlation continues back through Earth's history.

    4. Neighbor planets Mars and Venus are strikingly different, and their differences help confirm the theory of the greenhouse effect.

E. Cycling of materials plays a role in climate, with the most important cycles being those of water and carbon.

    1. The carbon cycle involves rapid cycling of carbon between atmospheric carbon dioxide and the biosphere, soils, and ocean surface waters.
    2. Carbon added to this system stays there for centuries to millennia and adds to the atmospheric carbon content.

Suggested Reading:

Houghton, chapter 3 through p. 39.

Wolfson, chapter 13, section 5.

Going Deeper:

Harvey, chapter 2, sections 3–4.

IPCC 4, chapter 7, first two sections.

Web Sites to Visit:

Hadley Centre. Thorough discussion of the carbon cycle.
http://www.metoffice.gov.uk.

Questions to Consider:

1. What is the biological pump, and how does it help remove carbon from the Earth–atmosphere–surface ocean system?
2. A typical molecule of carbon dioxide remains in the atmosphere for only about five years. Why, then, does the addition of CO_2 cause the atmospheric carbon dioxide concentration to remain increased for hundreds to thousands of years?

Lecture Seven

The Human Factor

Scope: For the past few centuries, we humans have been removing fossil carbon from the ground and burning it to provide energy. That process combines carbon with oxygen to produce carbon dioxide, which we release to the atmosphere through our tailpipes and smokestacks. About half that CO_2 accumulates in the atmosphere, with the result that atmospheric carbon dioxide has risen nearly 40% since the start of the industrial era—to levels the planet hasn't seen in at least a million years. We've released additional carbon through deforestation and agricultural practices, and land-use changes have altered the reflection of sunlight. All these processes affect Earth's climate, and recent climate change cannot be explained without including the human factor.

Outline

I. We begin with another quick review.

- **A.** The preceding lecture introduced the natural carbon cycle and showed how any additional carbon gets "stuck" in the rapidly cycling atmosphere–biosphere–surface ocean part of the cycle for hundreds to thousands of years.
- **B.** Earlier lectures showed how atmospheric carbon dioxide contributes to the natural greenhouse effect. Past climates show a strong correlation between atmospheric carbon dioxide concentration and global temperature. The science of the greenhouse effect shows why we should expect this correlation.

II. Now we explore the human influence on climate, concentrating first on our alteration of the carbon cycle.

- **A.** We're interested in this impact because human CO_2 emissions should lead to an *enhanced greenhouse effect* and, thus, to global warming.
- **B.** The dominant source of *anthropogenic* (human-produced) carbon in the atmosphere is the combustion of fossil fuels.
  - **1.** Fossil-fuel combustion results in about 7 gigatonnes (Gt, billions of tonnes) per year of carbon being emitted to the

atmosphere in the form of CO_2. We can represent this anthropogenic CO_2 by an additional arrow in the carbon cycle, from the fossil-fuel reservoir to the atmosphere.

2. Additional emission of roughly 2 Gt of carbon per year results from deforestation.
3. About half the emitted carbon ends up adding to the atmospheric carbon dioxide concentration. The rest is taken up by biosphere, soils, and ocean waters.
4. Although 7 Gt/year is small compared with natural carbon-cycle flows (for example, 110 Gt/year for photosynthesis alone), the anthropogenic carbon accumulates in the system.
5. The result of anthropogenic emissions is an increase in atmospheric carbon from a pre-industrial value of about 560 Gt to about 800 Gt today.
6. The corresponding concentration increase is from a pre-industrial value of about 280 ppm to around 390 ppm. That's roughly a 40% rise. See Figure 10.

C. How well do we know the history of atmospheric CO_2?

1. CO_2 is easier to measure than temperature; air bubbles trapped in ice provide past concentrations.
2. For the past half century, we've had direct measurements of atmospheric CO_2. See Figure 10 detail.

D. How do we know that the CO_2 of the past few centuries is anthropogenic?

1. Fossil fuels are commercial commodities. We have a good estimate of how much has been burned, and the CO_2 increase is consistent with this.
2. Fossil carbon has been buried for hundreds of millions of years. Therefore, it's depleted in the radioactive isotope carbon-14. Furthermore, living things take up stable carbon-12 more readily than they do stable carbon-13, and living things are the origin of the fossil fuels. Therefore, fossil carbon is also depleted in C-13. Examination of the isotopic composition of atmospheric carbon shows that it is becoming increasingly depleted in C-13 and C-14, indicating the fossil origin of the added carbon.
3. The oxygen content of the atmosphere is decreasing slightly, consistent with the oxidation of carbon through combustion.

E. How unusual is the industrial-era rise in atmospheric CO_2?

  1. Going back 1000 years with ice-core data shows that the industrial-era rise is unusual in the millennial context and coincides with the recent unprecedented rise in temperature.
  2. Going further back with ice-core data shows that the present-day CO_2 concentration is unprecedented over hundreds of thousands of years. Indirect evidence suggests that it is unprecedented in 20 million years. Quantitatively, today's CO_2 concentration is some 30% higher than anything the planet has seen in such long times. See Figure 11.

III. Anthropogenic CO_2 probably accounts for about half of the human impact on climate since the pre-industrial era. There are a number of other so-called *forcing agents* that also upset Earth's energy balance.

A. Methane (CH_4, natural gas) is another important greenhouse gas.

  1. On a per-molecule basis, methane is about 26 times more effective in blocking infrared radiation than is carbon dioxide.
  2. However, there's a lot less atmospheric methane, and its lifetime in the atmosphere is only about 12 years before chemical reactions remove it permanently.
  3. Methane has many sources, both natural and anthropogenic. The latter include leaks from mining and natural gas transport, agriculture, landfills and sewage treatment plants, rice paddies, and even hydroelectric dams. The sizes of anthropogenic methane sources are less understood than those of carbon dioxide, but methane probably contributes about one-third as much as CO_2 to global climate change.

B. Other significant greenhouse gases include nitrogen oxides, halocarbons, and ozone (O_3). Ozone has a warming effect in the lower atmosphere but a cooling effect in the stratosphere.

C. Anthropogenic *aerosols*—airborne particulates—also exert an effect on climate.

  1. Some aerosols result in warming, but the dominant aerosol effect is a cooling. The effect of most aerosols is more localized than that of greenhouse gases.
  2. Especially important are *sulfate aerosols*, resulting primarily from coal combustion. These reflect sunlight and, therefore, decrease the inflow of solar energy, upsetting Earth's energy balance in favor of cooling.

    3. Aerosols also influence cloud formation. Clouds are the least well understood aspect of the climate system, and this effect is highly uncertain. Some clouds absorb infrared, which results in warming, but the dominant effect of clouds is probably reflection of sunlight, resulting in cooling. This is the *indirect aerosol effect*.

  D. Another important human influence on Earth's energy balance is land-use changes that result in changes in reflected sunlight. The net effect here is uncertain but probably entails a slight cooling.

  E. For comparison, an important natural driver of climate change is variation in the Sun's energy output. This effect is small compared with the dominant human influences.

IV. Why do we attribute recent global warming to human activities?

  A. Records of atmospheric carbon dioxide and temperature show a strong correlation, with both rising at unprecedented rates in recent decades.

  B. More quantitative studies look at correlations between observed temperatures and the natural and anthropogenic influences on climate.

    1. Natural influences include volcanoes, solar variability, and fluctuations inherent in the complex climate system.

    2. Anthropogenic influences include greenhouse gases (warming) and aerosols (cooling).

    3. Results show that natural causes can explain the pre-20th-century temperature record but that the dominant correlation in the 20th century is with anthropogenic causes.

  C. Computer climate models are started from past conditions and run to the present. See Figure 12.

    1. Models that don't include anthropogenic effects satisfactorily reproduce observed climate into the mid-20th century.

    2. Only models that include anthropogenic effects can reproduce the climate of the late 20th century.

V. Let's close this lecture with a brief summary.

  A. Human activities, especially the burning of fossil fuels, are adding carbon dioxide to the atmosphere. This upsets Earth's energy balance in favor of warming. Today's atmospheric CO_2

concentration is nearly 40% above its pre-industrial value and is far above anything the planet has seen for nearly a million years and probably longer.

B. Other anthropogenic greenhouse gases, aerosols, and land-use changes also contribute. Greenhouse gases produce a warming; the net effect of aerosols and land-use changes is cooling. The latter effects are quantitatively quite uncertain.

C. Natural effects can explain climatic variations into the early 20th century, but only with anthropogenic greenhouse gases and aerosols can scientists explain the climate change of recent decades.

Suggested Reading:

Houghton, chapter 3, p. 42 to end.

Wolfson, chapter 14, section 14.3, "Attribution."

Going Deeper:

Harvey, chapters 7–8 (very technical).

IPCC 4, chapter 9.

Web Sites to Visit:

RealClimate. This blog, maintained by scientists active in climate research, has technically accurate, detailed discussions of climate issues and, particularly, the attribution of climate change to human activities. Search the site on "attribution" for discussions relevant to this lecture. http://www.realclimate.org.

Questions to Consider:

1. Human carbon dioxide emissions are a small fraction of the global carbon flows. Why, then, do we expect them to have a significant impact on climate?
2. In what way do pollutants emitted from coal combustion actually help to counter (but not prevent) anthropogenic global warming associated with greenhouse gases?

Lecture Eight

Computing the Future

Scope: Climate models explore how climate behaves in response to human-induced changes and natural factors. Some models are simple schemes that look only at global average temperature. Others are complex, dividing Earth's surface, atmosphere, and oceans into small cells and computing physical, chemical, and biological processes in each cell, as well as exchanges of matter and energy among cells. Models also incorporate *feedbacks*, whereby a change in one factor leads to effects that can either exacerbate or mitigate the original change. Climate models make a range of projections, but most suggest that we can expect a global temperature rise of several degrees Celsius over the next century.

Scientists have confidence in their models because they successfully reproduce today's climate starting from past conditions; because they predict climate change resulting from volcanic eruptions; and because they reproduce patterns of precipitation, barometric pressure, winds, ice and snow, and other observed features of Earth's climate. But we still don't understand every detail of climate, and we can't know future human behavior; thus, models cannot give us precise predictions of future climate. Nevertheless, different models agree that we should expect a general warming, and they agree on many details, as well.

Outline

I. *Climate models* are mathematical descriptions of Earth's climate system. They provide projections—not predictions—of future climate given a set of starting conditions and assumptions about future emissions of greenhouse gases and other factors. There's a hierarchy of models, increasing in complexity. All are useful for understanding the climate system.

A. The simplest models treat Earth as a single point and provide only a global average temperature, as in the simple calculation of Lecture Four.

B. Two-box models treat surface and atmosphere separately, accounting for the flows of energy between the two, as well as energy input from the Sun and infrared energy radiated to space.

C. More complex models include variations with latitude and may have many layers of ocean depth and height in the atmosphere.

D. The most complex models, called *GCMs* (for *global climate model* or *global circulation model*), include realistic descriptions of Earth's continents and oceans in three dimensions. They divide Earth's surface, oceans, and atmosphere into many small *cells* and account for flows of energy and matter among the cells.

  1. There's a fourth dimension: time. Some models provide only *equilibrium* climate projections, while others track the evolution of climate change through time.

  2. *Coupled models* use separate modules for different aspects of the climate system—oceans, the carbon cycle, the cryosphere, and so on. They're coupled through the exchanges of matter and energy between the different modules.

II. Models aren't perfect, for a variety of reasons.

A. Their *resolution* is limited.

  1. Even the best global models have grid cells about 100 miles on a side, and they may divide oceans and atmosphere into 20–40 layers. That makes for several million cells, each with many equations describing processes in that cell and its interactions with adjacent cells. Those equations must be solved repeatedly as the model steps forward in time.

  2. Global climate models tax even the fastest computers, which can advance the model climate some 5–10 years in 24 hours of computation time. That's one reason simpler models are often used for exploring ranges of future climate scenarios.

  3. *Moore's law*—the exponential increase in computing power that has computer speed doubling roughly every 18 months—allows ever finer resolution and gives us ever more powerful and accurate climate models.

B. We don't understand the details of every climate process. For this reason, climate models aren't based entirely on first principles but include some processes that are modeled on the basis of observational data.

- **C.** Some climate processes occur at scales below the grid-cell size. These are handled by approximate schemes called *sub-grid parameterization*.
  - **1.** Clouds such as cumulus are much smaller than the grid size. A crude way to handle a partly cloudy day is to assume a uniform cover of partially transparent clouds over a whole grid cell. More sophisticated parameterizations account for the vertical structure of clouds and the presence of clear sky between clouds, without actually resolving these features.
  - **2.** Such features as cities, lakes, forests, and agricultural lands may be smaller than the grid size. Their different climatic effects must also be parameterized.

III. *Feedback effects* are an important aspect of the climate system, and climate models must incorporate these effects.

- **A.** A feedback effect is an additional change that occurs following some change in a system.
  - **1.** If the additional change enhances the original change, then the feedback is a *positive feedback*.
  - **2.** If the additional change opposes the original change, then the feedback is a *negative feedback*.
- **B.** Many feedbacks operate in the climate system. Three of the most important include:
  - **1.** Ice-albedo feedback, in which a warming results in the melting of ice and snow, both of which reflect sunlight. (*Albedo* means reflectivity.) The darker land or ocean that's exposed absorbs more solar energy, resulting in still further heating. Ice-albedo feedback is one of the reasons why polar regions show the greatest temperature increases. This is a positive feedback.
  - **2.** Cloud-albedo feedback, in which warming results in increased evaporation and, thus, more clouds. But clouds reflect incoming sunlight, lowering the energy input to Earth and countering the initial warming. This is a negative feedback.
  - **3.** Water-vapor feedback, in which warming results in increased evaporation and, thus, more atmospheric water vapor. Because water vapor is a greenhouse gas, the effect is additional warming. This is a positive feedback and is estimated to

    increase the effects of anthropogenic greenhouse warming by some 50%.

- **C.** Some feedbacks may involve human behavior. For example, in response to warming, people buy more air conditioners. That means more coal is burned to generate electricity, and that means more carbon dioxide emission. That further enhances the greenhouse effect, leading to more warming. Thus, this is a positive feedback.
- **D.** Although negative feedbacks counter a warming effect, it's possible to show mathematically that they can reduce the effect but not reverse it—at least for situations in which the climate responds gradually (linearly) to changes.
- **E.** Feedbacks work in either direction. For example, a cooling of the planet results in more ice and snow, thus more reflection of sunlight, and thus, further cooling. This is, again, the positive ice-albedo feedback.

IV. *Model validation* procedures give scientists confidence in their climate models.

- **A.** Climate models started with past conditions successfully reproduce present-day climate, as discussed in the preceding lecture.
- **B.** Climate models reproduce many details of Earth's climate, including:
    - **1.** Temperature structure of the atmosphere.
    - **2.** Geographical distribution of precipitation.
- **C.** Future climate projections show consistency.
    - **1.** All show temperature increases with increasing atmospheric CO_2.
    - **2.** However, projections show a considerable range in values of projected temperature changes.
- **D.** We can't experiment with Earth's actual climate, but nature can—in the form of volcanic eruptions that inject enough dust into the atmosphere to affect global climate. Climate models successfully describe the resulting impact on global temperature. See Figure 14.

Suggested Reading:

Houghton, chapter 6 through p. 128.

Wolfson, chapter 15, sections 1–2.

Going Deeper:

IPCC 4, chapter 8.

Ruddiman, chapter 3.

Web Sites to Visit:

Climate Prediction Experiment. Participate in a worldwide climate modeling experiment! ClimatePrediction.net harnesses the spare computing power of personal computers worldwide to run multiple simulation experiments using the world's most sophisticated climate models. You can sign your own computer up to participate and keep yourself posted on the results of the ClimatePrediction experiments.
http://www.climateprediction.net.

Questions to Consider:

1. Why is it useful to have a hierarchy of climate models, from the simplest to the most complex computer models?
2. How did the Mount Pinatubo eruption give climate modelers a natural experiment with which to test their models?

Lecture Nine

Impacts of Climate Change

Scope: A rise in the global average temperature is just one aspect of anthropogenic climate change. The temperature rise itself will not spread evenly over the globe; for example, it will generally be greater over land and at high latitudes. Extreme events, such as heat waves, intense precipitation, and droughts, will be more frequent, and storm intensities will likely increase. As ocean water heats, it expands, and this effect will raise sea level. Melting glaciers and land-based ice will augment sea-level rise. Although melting sea ice will have little direct effect on sea level, freshwater from such melting might disturb patterns of ocean circulation, such as in the Gulf Stream, possibly resulting in sudden "surprise" changes in climate. Absorption of anthropogenic carbon dioxide makes the oceans more acidic, putting shell-forming organisms at risk. Many of these changes have feedback effects that can further exacerbate the impact of climate change.

Outline

I. The most obvious effect of climate change is a rise in the global average temperature.

- **A.** Future climate change depends on human activities, such as greenhouse gas emissions and patterns of land use. For this reason, projections of future climate take the form of different scenarios based on different assumptions about human behavior.
  - **1.** A set of scenarios used by the Intergovernmental Panel on Climate Change (IPCC) describes the future of human society on a two-dimensional space. One dimension is economic versus environmental emphasis; the other is globalization versus regional differences.
  - **2.** The different scenarios give different projections of future greenhouse emissions and global temperature. The projections for different scenarios are obtained by averaging over projections of many different computer models. These projections suggest a 21st-century global temperature increase in the range of 1.5°C to 4.5°C. Statistical analyses show that

there's little chance of the change being much lower than 1.5°C, but there's a non-negligible chance that it could be higher than 4.5°C. See Figure 15.

- **B.** Why should a temperature rise of only a few degrees have significant effects?
  - **1.** That few degrees is a *global average*. The rise will be more substantial in certain areas—particularly the polar regions and over almost all land areas.
  - **2.** Lecture Three showed how only about 6°C separates the present-day climate from the depths of an ice age. Thus, a few degrees in global temperature is climatologically significant.
  - **3.** Analysis of statistical distributions shows how even a small shift in the mean value of a quantity (such as temperature) makes a significant change in the likelihood of extreme events.

II. Extreme weather events, such as those listed below, will become more likely with increasing temperature.

- **A.** Heat waves. Although it's difficult to attribute any single event to anthropogenic climate change, statistical analysis of the 2003 summer heat wave in Europe that killed tens of thousands of people suggests that this event lies so far out on the normal distribution curve that there's at least a 50% chance it was caused by anthropogenic climate change.
- **B.** Intense precipitation events.
- **C.** Droughts.
- **D.** Intense tropical storms. Here, as often with climate change, a number of factors complicate the picture. Warming ocean waters should contribute to rising tropical storm intensity, and as warming penetrates deeper into the ocean, storms may become more robust because they're less likely to stir up cooler water from below. On the other hand, changes in wind patterns might shear apart nascent storms before they can become fully formed.

III. Sea-level rise is one of the most important long-term impacts of climate change. Measuring sea level is difficult because the sea surface isn't flat, because of tidal variations, and because the continental edges are themselves rising in some places and falling in others. Earlier measurements come from tide-gauging stations; modern measurements, from satellites.

A. During the last ice age, sea level was some 120 meters (about 400 feet) below its current level. The oceans rose rapidly as ice melted, but by 6000 years ago, the rate of rise had slowed to about 0.1 to 0.2 millimeters per year.

B. Sea-level rise today is caused primarily by two factors:
   1. Thermal expansion of the ocean waters as they warm.
   2. Melting of land-based glaciers and ice sheets. Melting of floating sea ice contributes almost nothing to sea-level rise, although it may have other effects.
   3. Other contributions to sea-level rise include melting permafrost and human alteration of the water cycle. "Mining" groundwater for human use adds to sea-level rise, while dams block natural flows and keep water from reaching the oceans.
   4. As usual, there are complicating factors. For example, increased precipitation may lead to more snow in polar regions. In the very cold Antarctic interior, this effect actually removes water from the oceans, slowing the increase in sea level.

C. The 20th century saw sea level rise at about 1–2 millimeters/year—some 10 times its rate in the past few millennia.

D. Projections suggest a global sea-level rise in the range of 6 to 18 inches by 2100 for the A1 balanced scenario.
   1. Sea-level rise will be greater if we continue with a fossil fuel–intensive economy.
   2. Sea-level rise has a long lag time; thus, even if greenhouse emissions stopped, we would be committed to another roughly half a meter (20 inches) over the next few centuries.

E. A rise of a foot or so doesn't sound like much, but this adds to already high tidal levels and storm surges.
   1. Sea-level rise will have a significant impact in low-lying areas, such as barrier islands, Florida, and Bangladesh—which could lose some 10% of its land area.
   2. Rising sea level forces saltwater into underground aquifers and marine estuaries, contaminating water supplies in coastal areas and damaging the "nurseries" for many marine species.

IV. The poleward advance of species ranges discussed in Lecture Two will accelerate.

  A. Some species, especially trees, may not be able to keep up with the changes. They, and ecosystems that depend on them, may cease to exist in many areas and some may even go extinct.

  B. Tropical species, including disease vectors, will spread into temperate regions. Such diseases as malaria, Lyme disease, West Nile virus, and Dengue fever may become more widespread.

V. Uptake of anthropogenic carbon dioxide in the oceans results in acidification of the ocean water. This may affect the survival of shell-forming marine plankton, which serves as the basis of marine food chains. Such effects will first occur at high latitudes, and then spread equatorward.

VI. "Surprise" events may occur if the climate system responds with nonlinear "tipping point" behavior.

  A. An example of nonlinear behavior is a light switch: Moving the lever gradually doesn't do anything for a while; then, the switch suddenly jumps to the "on" position and the light goes from off to full brightness.

  B. Catastrophic "surprise" events aren't considered likely during the 21st century, but their probability will rise considerably after the year 2100.

  C. One such nonlinear "surprise" could be the sudden slipping of a large land-based ice sheet into the sea.

    1. Possible causes include the lubrication of the ice-land interface by increased meltwater flowing below the ice and the melting or breakup of sea ice that helps keep land-based ice from sliding into the sea.

    2. The West Antarctic ice sheet is of particular concern; this would raise sea level abruptly by some 3 meters, or about 10 feet.

  D. A second nonlinear "surprise" would be a major upset in patterns of ocean circulation.

    1. One possible cause would be the injection of freshwater into the northern North Atlantic as a result of the melting of sea and land ice. This effect is already weakening the so-called *thermohaline circulation* that transports warm surface water toward northern Europe.

2. An abrupt shutdown of the thermohaline circulation could, ironically, cause Europe to cool in response to global warming. However, images of a European deep freeze are probably unrealistic. Nonetheless, we still have a lot to learn about ocean circulation.

VII. Effects on human society and the global economy are beyond the scope of this science-based course. But one recent study suggests that climate change in the coming decades could reduce the global economy by some 20% unless major steps are taken to curb greenhouse emissions and other climate-changing activities. Acting now might cost just 1% of global economic output.

Suggested Reading:

Houghton, chapters 6–7.

IPCC 4, Summary for Policymakers.

Wolfson, chapter 15, section 15.2 to end.

Going Deeper:

IPCC 4, Technical Summary.

Stern (see also Web Sites to Visit, below).

Stott, Stone, and Allen.

Web Sites to Visit:

British Treasury Department. From this site, you can download all or part of the 700-page Stern Review on the Economics of Climate Change. http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm.

Pew Center on Global Climate Change, Both the Economics and Environmental Impacts links found on this page carry more detailed information relevant to this lecture. http://www.pewclimate.org/global-warming-in-depth.

Questions to Consider:

1. A friend asks how a rise of a few degrees in global temperature can possibly have a significant effect given that daily temperatures frequently vary by more than 10 times that much. How do you answer?
2. This lecture concentrated on physical, biological, and ecological effects of climate change. In what ways might these effects have an impact on human society?

Lecture Ten

Energy and Climate

Scope: Humankind's thirst for energy is the dominant reason for our increasing influence on Earth's climate. The world uses energy at the prolific rate of about 15 trillion watts. In North America, per capita energy consumption is more than 100 times our own bodies' energy output. We use energy for a range of purposes that enhance our quality of life, from keeping warm to providing mobility to powering industry. Nearly all of humankind's energy comes from the fossil fuels coal, oil, and natural gas. Burning these fuels naturally releases carbon dioxide, which is not a pollutant in the traditional sense but, rather, an expected and, indeed, desired product of fossil-fuel combustion. The result is the 7 gigatonnes of fossil carbon released into the atmosphere annually, as described in Lecture Seven. The high living standards of industrialized countries are closely related to energy consumption.

Outline

I. Humanity uses energy at the rate of 15 trillion watts—the equivalent of 150 billion 100-watt light bulbs.

A. The *watt* measures *power*—the *rate* of energy consumption or generation. That 15 trillion watts can be expressed in many equivalent ways:

1. In English units, that's nearly 500 quadrillion BTUs per year.

2. It's the energy equivalent of some 80 billion barrels of oil per year (actual oil consumption is about 30 billion barrels per year), or more than 2500 barrels of oil every second.

3. For scientists, it's about 5×10^{20} joules every year (500 EJ/year).

B. Per capita energy consumption is correspondingly large.

1. With world population nearing 7 billion, that 15 trillion watts is more than 2000 watts per person.

2. By metabolizing food, the average human body produces energy at the rate of about 100 watts. On average, then, each human uses energy at about 20 times his or her own body's energy output.

        3. Energy consumption is far from uniform over the globe. In the most energy-intensive countries, it exceeds 10,000 watts (10 kW) per capita, the equivalent of more than 100 human bodies' worth of energy.

II. What do we do with all this energy? Four sectors—industrial, transportation, residential, and commercial—account for nearly all our energy use.

- **A.** In the United States, where we have about 100 "energy servants" each, you can think of the percentage of energy use in each sector as the number of servants in that sector.
- **B.** Some 28 energy servants are at work round the clock to transport you and the goods you use.
- **C.** Another 32 labor on your behalf in industry.
- **D.** Some 22 are at work in your home, keeping you warm or cool; making hot water; cooking; and running lights, entertainment systems, and computers.
- **E.** The commercial sector employs some 18 energy servants, keeping on the lights, copiers, and computers in offices, hospitals, and educational institutions and running the lights, freezers, and cash registers in our supermarkets and stores.

III. Who are our energy servants? They're the mix of sources that we use to produce energy. See Figure 16.

- **A.** Some are fuels, substances that store energy. These include fossil and nuclear fuels, as well as fuels made from biological materials.
- **B.** Others are tapped from natural flows of energy. These include the energy of flowing water, wind, and tides and currents, and the nearly steady flow of energy from the Sun.
- **C.** Expect much more on fuels and energy flows in the next lecture.
- **D.** The mix of energy sources differs from country to country, depending on the country's resources or its wealth and, therefore, its access to imported energy.
    - **1.** In both the United States and the world as a whole, the fossil fuels coal, oil, and natural gas provide the overwhelming

contribution to the energy supply, approaching 90% in both cases.

2. Although this pattern holds throughout most of the world, there are exceptions. For example, France gets a significant fraction of its energy from nuclear sources; Norway, Congo, and Brazil, from water power; and Iceland, from geothermal sources.

E. The climate connection: Fossil-fuel combustion and other fossil energy–related activities are responsible for some 83% of U.S. greenhouse gas emissions.

1. CO_2 from combustion of fuels dominates the greenhouse emissions related to fossil fuels; other energy-related sources include methane leaks from natural gas systems, refinery emissions, and methane from active and abandoned coal mines.
2. Significant sources not related to energy production include methane from landfills and agriculture, carbon dioxide from cement production, methane from sewage treatment, and many industrial processes.
3. Included in these figures are the effects of land-use "sinks" that remove CO_2 from the atmosphere.

IV. What does our prolific energy consumption buy us? (We're moving out of pure science but staying quantitative!)

A. For many countries, there's a direct correlation between energy consumption and material well-being, as measured by the gross domestic product (GDP). See Figure 13.

B. But some countries are less efficient in their use of energy, producing lower GDP for a given rate of energy consumption. Others are more efficient.

C. Overall, a sample of many countries shows a general correlation between energy consumption and GDP.

D. But some economists question the GDP's appropriateness as a measure of human well-being. An alternative, the United Nations' Human Development Index (HDI), shows an initial rise with increasing energy consumption but then a leveling off, after which more energy consumption does not increase a country's HDI.

Suggested Reading:

Smil 2006, chapters 1–4.

Wolfson, chapter 2.

Going Deeper:

Smil 2003, chapters 1–2.

Web Sites to Visit:

International Energy Agency (IEA). This site lets you generate energy data for your choice of country, region, and energy type from the IEA's vast database. A click on the Key Statistics link gets you to a free download of the annual *Key World Energy Statistics*.
http://www.iea.org/Textbase/stats/index.asp.

U.S. Department of Energy, Energy Information Administration, *Annual Energy Review*. Published yearly and made available on the Web, the *Annual Energy Review* is a comprehensive compilation of energy statistics for the United States. There's a less detailed section entitled "International Energy." Most of the data are displayed in both tables and graphs, and the tables are available for download as spreadsheets.
http://www.eia.doe.gov/emeu/aer/.

U.S. Department of Energy, Energy Information Administration, *International Energy Annual.* A more comprehensive compilation of international energy statistics. http://www.eia.doe.gov/iea/.

U.S. Environmental Protection Agency (EPA), "Greenhouse Gas Emissions." This EPA site is an authoritative source for detailed statistics on U.S. greenhouse gas emissions.
http://www.epa.gov/climatechange/emissions/index.html.

Questions to Consider:

1. If you're a resident of North America, you've got something more than 100 energy servants working for you, round the clock. Roughly how many are "working" in (a) transportation, (b) industry, (c) commerce, (d) your home?
2. Energy consumption is the dominant cause of anthropogenic climate change. What are some others?
3. Discuss how a country's energy consumption relates to its standard of living.

4. Find out where most of your electrical energy comes from. This will vary from country to country and from state to state within the United States and may even depend on your particular municipality or power company.

Lecture Eleven

Energy—Resources and Alternatives

Scope: The fossil fuels that supply most of the world's energy have many deleterious environmental impacts, of which climate-changing greenhouse emissions are but one. Unless we can keep fossil-fuel carbon emissions out of the atmosphere, the challenge of climate change dictates that we find alternatives. Earth's natural systems offer a number of alternatives, broadly classified as *flows* and *fuels*.

Nuclear fission provides nearly greenhouse-free energy, but for the near future, it can't help with transportation. And it faces serious questions of economics, waste disposal, and weapons proliferation. Less developed alternatives have their advocates, but some—such as geothermal and tidal energy—are limited resources. Others, such as nuclear fusion, are too uncertain to count on. Solar-based technologies—including direct use of sunlight and indirect applications, such as wind, hydropower, and biomass—have the advantage of tapping Earth's dominant energy flow. Ultimately, a sustainable civilization will need to use these sources, but they won't be available overnight. For this reason, we need to introduce new energy technologies while using less energy.

Outline

I. If we want to avoid serious climate change and we can't eliminate carbon emission from fossil fuels, then we'll have to find alternative approaches to our energy supply. Earth's natural systems provide us with several distinct energy resources. This lecture is a brief survey of those energy resources and the technologies that exploit them. See Figure 17.

  A. *Flows* are streams of energy that arrive continuously at Earth's surface.

    1. By far, the most dominant flow is solar energy, which constitutes 99.98% of the energy reaching Earth. Solar energy drives subsidiary flows, including wind and flowing water, and through photosynthesis, powers nearly all life on Earth.

2. Nearly all the remaining 0.02% of Earth's natural energy flow is geothermal energy from Earth's hot interior.
3. A tiny fraction of Earth's energy flow is from tidal energy, ultimately originating in the motions of the Earth and Moon.

B. *Fuels* are substances that store energy, generally in Earth's interior.

1. The *fossil fuels* coal, oil, and natural gas are "stored sunlight," their carbon-based chemical structure storing solar energy that was trapped tens to hundreds of millions of years ago through photosynthesis.
2. *Nuclear fuels* are substances that can release energy through nuclear reactions. Of the naturally occurring nuclear fuels, we currently use only uranium to produce energy, through the process of nuclear fission. But deuterium, a heavy isotope of hydrogen in ocean waters, carries almost unlimited energy that could be released in the process of nuclear fusion.

II. We have technologies to tap most but not all of Earth's energy flows and fuels. Some technologies are more mature and more economically viable than others. And some of Earth's energy resources are simply inadequate to supply more than a small fraction of humanity's current energy demand.

A. Combustion of fossil fuels is an established technology for both stationary and transportation energy.

1. Efficiency of large-scale fossil-fueled electric power generation is typically around 40%.
2. More advanced fossil technologies approach 60% and may cogenerate both heat and electric power.
3. Fossil-fueled internal combustion engines for vehicles are only about 15% efficient in converting fuel energy to mechanical energy of the wheels.
4. Fossil fuels, except coal, are in limited supply, and all produce the greenhouse gas carbon dioxide, as well as a host of harmful pollutants.

B. Geothermal and tidal energy flows, although significant in a few localized regions, simply aren't adequate for humanity's energy supply.

C. Nuclear energy currently supplies about 6% of the world's energy, nearly all of it in the form of electricity, making it one of two alternatives to fossil fuels that have demonstrated their ability to produce energy on large scales.

1. Nuclear energy may be produced either from *fission* of heavy elements, such as uranium, or *fusion* of light elements.
2. Nuclear reactions are concentrated sources of energy, releasing about 10 million times as much energy as chemical reactions, such as the burning of fossil fuels.
3. So far, we've learned to harness only nuclear fission for useful energy generation. Fission of uranium powers our nuclear power plants.
4. Nuclear fission produces radioactive waste, some of which will remain dangerous for tens of thousands of years or more. But the quantities are relatively small compared with the effluents from fossil-fuel combustion.
5. Although there is considerable anxiety over the safety of nuclear energy, nuclear power plants almost certainly have far fewer detrimental effects on human health and the environment than comparable fossil fuel facilities.
6. But issues of long-term waste disposal and, especially, the relation of nuclear power to weapons proliferation, cast a cloud over nuclear power's future.
7. Finally, nuclear fission as it's used today cannot meet the energy needs of our transportation systems.
8. Energy from nuclear fusion remains an elusive technological goal, although fusion research is slowly advancing. Technologically and economically viable fusion reactors would give us almost unlimited energy with less environmental impact than either fossil fuels or nuclear fission. As a fusion fuel, each gallon of seawater contains the energy equivalent of about 300 gallons of gasoline!

D. Direct use of solar energy taps a flow that carries some 10,000 times more energy than humanity now uses.

1. Simple *passive solar* technologies allow for heating, cooling, and lighting of buildings using sunlight.
2. More complex *active solar* technologies use solar heating for space heating, water heating, and even the generation of electricity.

3. *Photovoltaic cells* offer direct conversion of solar energy into electricity with no moving parts.
4. Despite their long-term promise, direct solar energy technologies today are generally not economically competitive with conventional energy sources—especially for photovoltaics. But rapid progress may be changing that; worldwide, installed solar generating capacity is growing at some 40% per year.

E. Indirect solar energy sources include water, wind, and biomass.

1. Hydropower taps that portion of the solar flow that drives Earth's water cycle, using the energy of moving or falling water in rivers and at dams. Hydropower is tied with nuclear energy as the second most important source of humanity's energy after fossil fuels and is the other mature energy technology that has been demonstrated to work on a large scale. But most of the world's hydropower has long since been tapped, and new installations often involve major environmental and social disruption.
2. Wind power has considerable potential for generating electricity, and its use is growing rapidly. In the United States, the wind resource is more than enough to supply all the country's electrical energy—but because wind is intermittent, it's not practical to rely on wind for more than 20% of the electricity supply.
3. Combustion of biomass does not make a significant contribution to atmospheric greenhouse gases, provided the biomass is harvested sustainably and without substantial use of fossil fuel. Some biomass systems meet this criterion; others do not. For example, ethanol for motor fuels takes nearly as much fossil energy to produce as is obtained from its combustion. Liquid and gaseous biomass fuels are the one example of indirect solar energy that can be used to power transportation vehicles.

F. What about hydrogen?

1. Although hydrogen is, in many ways, an ideal fuel, producing only water when burned, Earth's energy resources don't include hydrogen.

        2. Hydrogen must, therefore, be made from other energy sources, which means that the environmental benefits or disadvantages of hydrogen are largely those of the energy sources used to produce it.
        3. Hydrogen-powered vehicles might play a part in a long-term energy future, provided hydrogen could be generated by carbon-free means, such as nuclear fission, nuclear fusion, wind, or solar energy.

III. No energy source is completely benign.

- **A.** The various alternatives to fossil fuels often involve energy-intensive manufacture or the use of toxic substances (solar photovoltaics), waste and safety issues (nuclear power), aesthetic and wildlife issues (wind), or pollutants and competition for cropland (biomass).
- **B.** All involve some greenhouse emissions, although much less than with fossil fuels. See Figure 18.

Suggested Reading:

Smil 2006, chapters 5–6.

Going Deeper:

Smil 2003, chapters 4–6.

Wolfson, chapters 5–11.

Web Sites to Visit:

Intelligent Energy Europe. This European Commission site features myriad links to programs and information related to the European Union’s vigorous pursuit of non-fossil energy. http://ec.europa.eu/energy/index_en.html.

National Renewable Energy Laboratory. At this U.S. Department of Energy site, you can find out about research into alternative energy technologies. http://www.nrel.gov/.

Questions to Consider:

1. Supporters of a “business-as-usual” energy strategy sometimes claim that solar energy isn’t practical because there isn’t enough of it. Is this true? In what sense is solar energy not an immediate solution to our energy problems?

2. What’s the difference between nuclear fission and fusion? What would be the fuel source for a practical fusion power plant?
3. Why do non-fossil energy sources entail some greenhouse gas emissions, albeit much less than with fossil fuels?

Lecture Twelve

Sustainable Futures?

Scope: Earth's future climate depends not only on science but also on human behavior. Climate models run with different scenarios for human population and energy use yield very different projections of future climate. Avoiding disruptive climate change probably means keeping atmospheric carbon dioxide to at most a doubling of its pre-industrial level. We can achieve that goal only through a substantial reduction in anthropogenic carbon emissions. Here, we have choices: We can continue to burn fossil fuels but capture and sequester the carbon dioxide produced. We can switch to energy sources that produce less carbon dioxide. We can use less energy. Practical strategies for mitigating climate change will most likely involve all three approaches. There are many paths to a stable climate, and we have the luxury of choice. But we don't have the luxury of time.

Outline

I. With regard to climate change, humanity's goal is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

- **A.** This goal was adopted at the 1992 Earth Summit in Rio de Janeiro and signed by nearly 200 countries, including the United States. The goal is embodied in the United Nations Framework Convention on Climate Change (UNFCC).
- **B.** Most climate scientists suggest that a threshold for "dangerous anthropogenic interference with the climate system" is somewhere around a doubling of pre-industrial atmospheric carbon dioxide.
  - **1.** The pre-industrial concentration was about 280 parts per million; therefore, a doubling would be 560 parts per million.
  - **2.** Today, we're at around 390 ppm, climbing by about 2 ppm per year.
  - **3.** A look at the IPCC scenarios suggests that we won't avoid "dangerous anthropogenic interference" if we continue with "business as usual." See Figure 19.

II. Given that the dominant anthropogenic effect on climate is from combustion of fossil fuels, we have four different ways to avoid that "dangerous anthropogenic interference."

- **A.** With global engineering projects, we could attempt to counter the effects of increasing greenhouse gases. But we really don't know enough about the complex workings of all Earth's systems to make this approach a wise one. Approaches that have been discussed include the following:
  - **1.** Injecting sulfur particles into the upper atmosphere to reflect sunlight.
  - **2.** Placing mirrors in orbit to reflect sunlight.
  - **3.** "Seeding" the oceans with iron to increase phytoplankton growth and, thus, take up carbon dioxide.
- **B.** We could continue to burn fossil fuels but prevent the resulting CO_2 from entering the atmosphere. This approach entails some form of *carbon capture and sequestration* (CCS).
  - **1.** CCS with conventional power systems is technologically and economically challenging because of the huge volumes of carbon dioxide produced—about 1000 tons each hour from a typical electric power plant. Furthermore, the carbon must be separated from large volumes of nitrogen that constitute most of ordinary air.
  - **2.** Newer schemes envision removing carbon before fuel is burned, typically by gasifying coal to form a mixture of carbon dioxide and hydrogen. The hydrogen would be burned, and the CO_2 would be sequestered.
  - **3.** Sequestering carbon means storing it where it can't escape to the atmosphere. Brine-containing sedimentary rock formations, abandoned oil fields, and the deep ocean have all been suggested as sequestration sites.
  - **4.** CCS can work only with large, stationary sources of CO_2, such as electric power plants and industrial boilers.
  - **5.** CCS has both economic and energy costs. It would take as much as 40% more fuel to produce a given amount of energy with CCS as opposed to conventional technology.
- **C.** We could switch from fossil fuels to the various energy alternatives discussed in the preceding lecture.

    1. Of those, only nuclear fission and hydroelectricity have demonstrated potential as large-scale energy sources, and both are currently suited only to electric power generation. The hydro resource is almost fully exploited, and an expansion of nuclear power faces waste disposal, safety, and weapons proliferation issues.
    2. Other alternatives, especially direct and indirect solar technologies, have considerable promise—but most aren't technologically or economically competitive with cheap fossil fuels at present.
    3. A distant future might feature a carbon-free energy economy using solar energy or nuclear fusion, with hydrogen produced for transportation fuel. But that's not a near-term solution.

  D. We could use less energy.
    1. This doesn't mean "freezing in the dark" but, rather, using energy more intelligently—getting energy's benefits without using as much energy.
    2. In the United States, we've already reduced our *energy intensity*—the energy required per unit of gross domestic product—by some 50% since 1975.
    3. During energy shortages, we've demonstrated our ability to reduce energy consumption. Had we continued such reductions, we would today be using far less energy and producing far lower greenhouse emissions.
    4. Many of our energy systems can be made far more energy efficient.
    5. Efficiency gains compound. For example, better home insulation means downsizing the heating system, lowering costs and energy required to manufacture the system. "Superinsulating" may eliminate the need for a heating system altogether. Similar gains abound in industrial applications.

III. There's no one solution to anthropogenic climate change. Instead, we'll need to use a range of energy options to reduce our greenhouse emissions.

  A. Here, we have choices—more than we actually need!

  B. A study by Stephen Pacala and Robert Socolow of Princeton University shows how the use of "wedges" from a wide range of choices can stabilize our greenhouse emissions. See Figure 20.

    1. In 50 years, each wedge will have prevented 7 gigatonnes of carbon from entering the atmosphere.
    2. Wedge choices include improving energy efficiency, substituting nuclear for coal-fired electric power plants, substituting natural gas for coal, using biofuels for transportation, implementing carbon capture and sequestration, planting trees in temperate climates, building 2 million wind turbines to replace coal-fired electric power plants, providing 2000 gigawatts of solar photovoltaic power production to replace coal, halting tropical forest deforestation, and restoring 300 million acres of damaged forest.
    3. The wedge approach isn't the complete solution to anthropogenic climate change, and it alone won't stabilize atmospheric CO_2. What the wedge approach does is to stabilize our emissions over the next 50 years. After that we need to start reducing emissions if we're to stabilize CO_2 levels at less than a doubling of its pre-industrial level.

IV. Review of the entire course.

- **A.** Global temperature is rising.
    1. The increase of recent decades is almost certainly attributable to human activities, especially the emission of carbon dioxide and other greenhouse gases. CO_2 levels are now some 30% higher than anything the planet has seen in hundreds of thousands to perhaps millions of years.
    2. Other climatic changes also point to an anthropogenic origin for present-day climate change.
- **B.** Computer models suggest an additional rise of 1.5°C to 4.5°C over the coming century. Impacts include rising sea level, more extreme weather events, droughts and floods, changes in species ranges, spread of tropical diseases, and less likely, sudden "surprise" changes in climate.
- **C.** Most of humanity's impact on climate comes from our combustion of fossil fuels for energy, which necessarily produces the greenhouse gas carbon dioxide.
    1. We will need to curtail atmospheric greenhouse emissions if we're to avoid "dangerous anthropogenic interference with the climate system."

2. Many approaches can work, including a mix of alternative energy sources, greater energy efficiency, and carbon sequestration.
3. But we need to act now.

Suggested Reading:

Houghton, chapter 11.

Wolfson, chapter 16.

Going Deeper:

IPCC 2005.

Lovins, et al.

Pacala and Socolow.

Web Sites to Visit:

Princeton Environmental Institute Carbon Mitigation Initiative. This Princeton University site provides a detailed description of the "wedge" approach to greenhouse stabilization, including a movie, a simulation game, and links to the original papers.
http://www.princeton.edu/~cmi/resources/stabwedge.htm.

Questions to Consider:

1. "Using less energy" often conjures up images of people shivering in bulky sweaters or crammed into impossibly tiny cars. Why are such images misleading?
2. Which seven wedges would you choose to stabilize our greenhouse emissions?

Figures

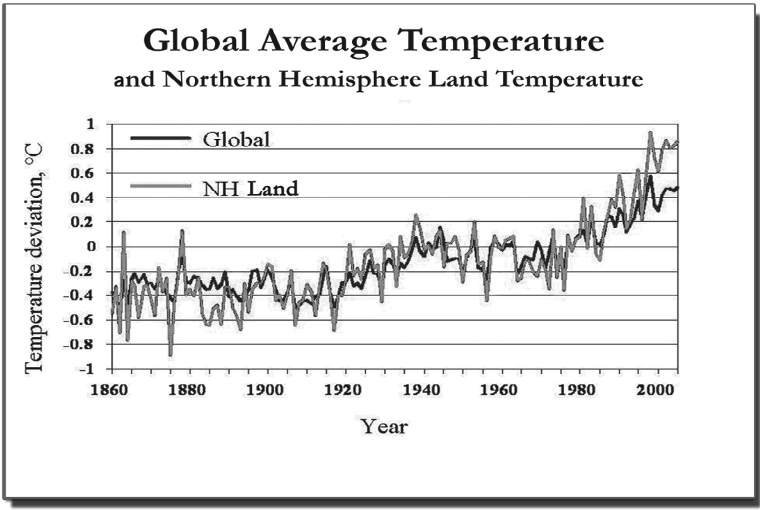


Figure 1

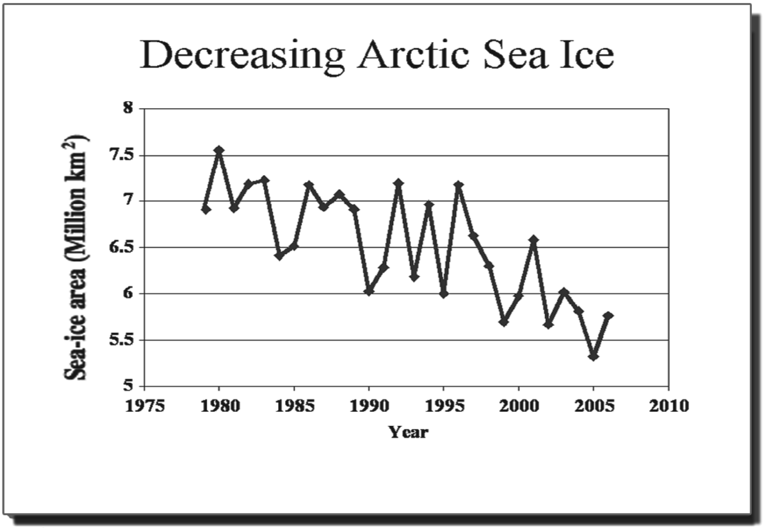


Figure 2

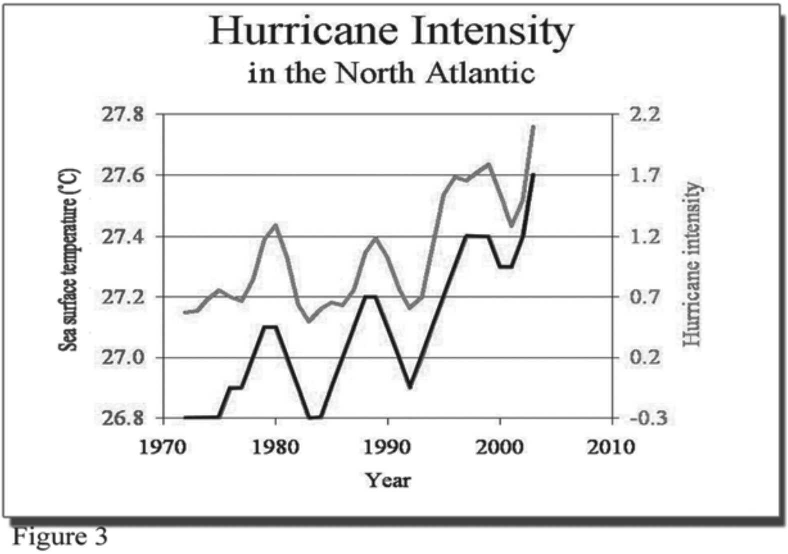


Figure 3

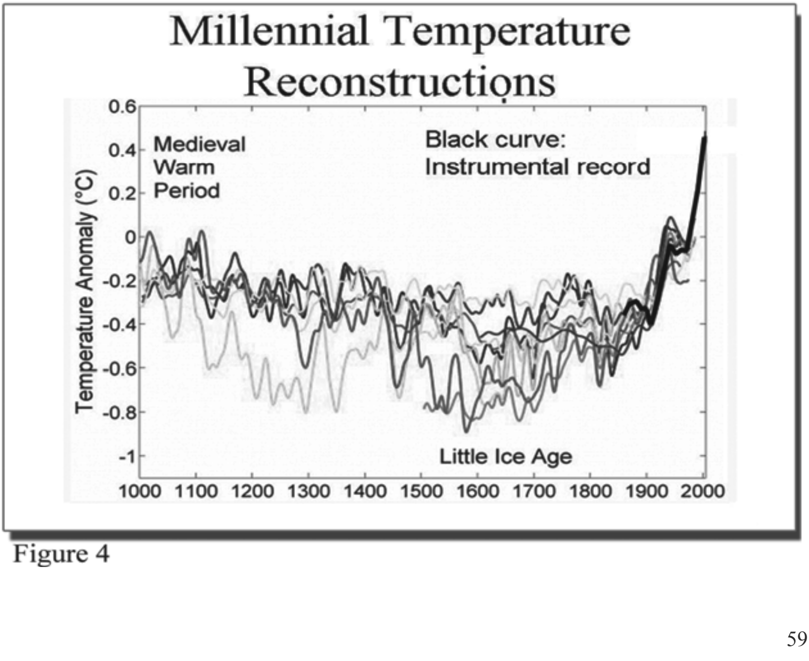
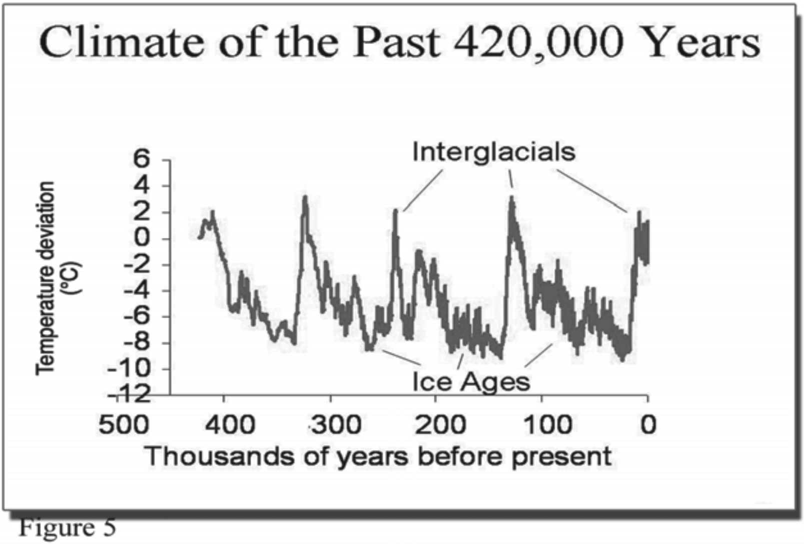
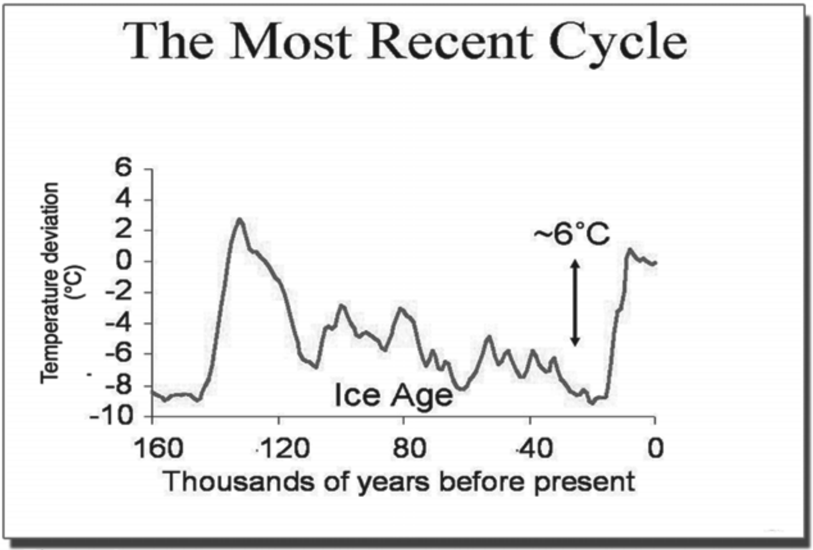


Figure 4



Climate of the Past 420,000 Years

Figure 5



The Most Recent Cycle

Figure 6

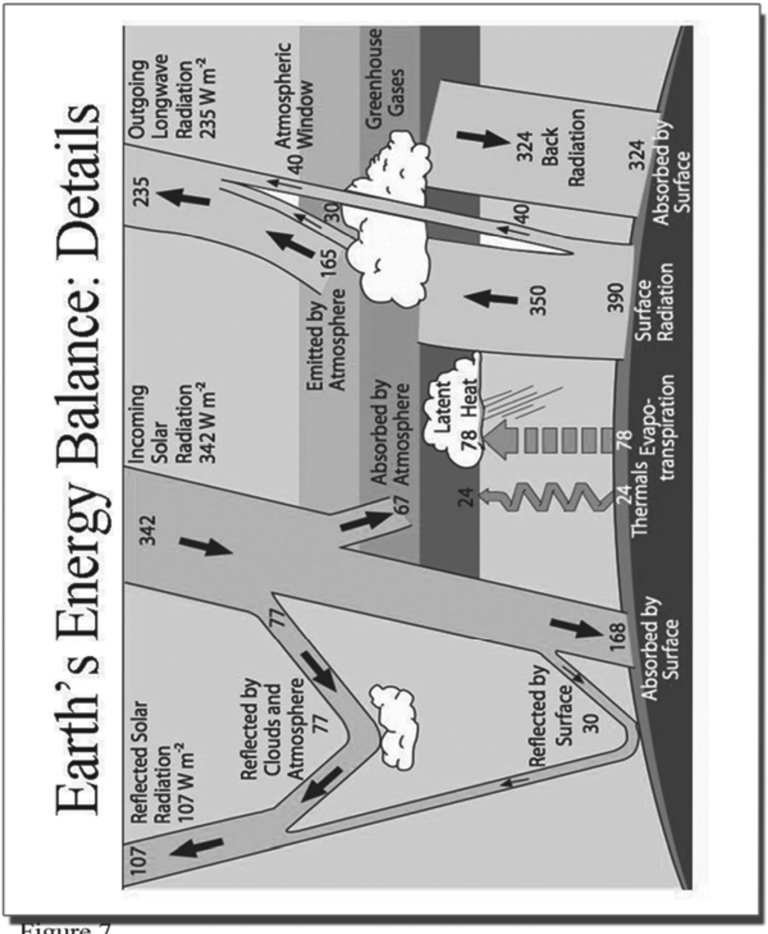

Earth's Energy Balance: Details
Reflected Solar Radiation 107 W m^{-2}
107
Reflected by Clouds and Atmosphere 77
77
Incoming Solar Radiation 342 W m^{-2}
342
67 Absorbed by Atmosphere
Reflected by Surface 30
168
Absorbed by Surface
24
Thermals
24
Latent 78 Heat
78
Evapo-transpiration
Emitted by Atmosphere
165
30
Outgoing Longwave Radiation 235 W m^{-2}
235
40 Atmospheric Window
Greenhouse Gases
350
390
Surface Radiation
40
324 Back Radiation
324
Absorbed by Surface

Figure 7

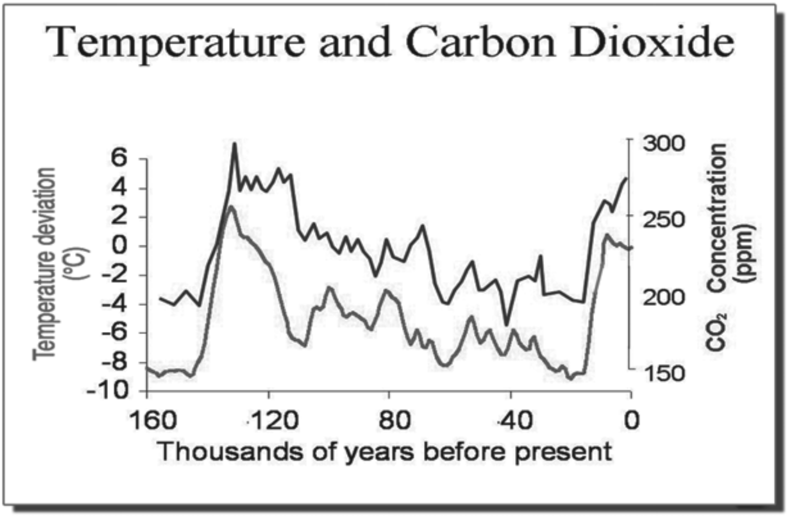


Figure 8

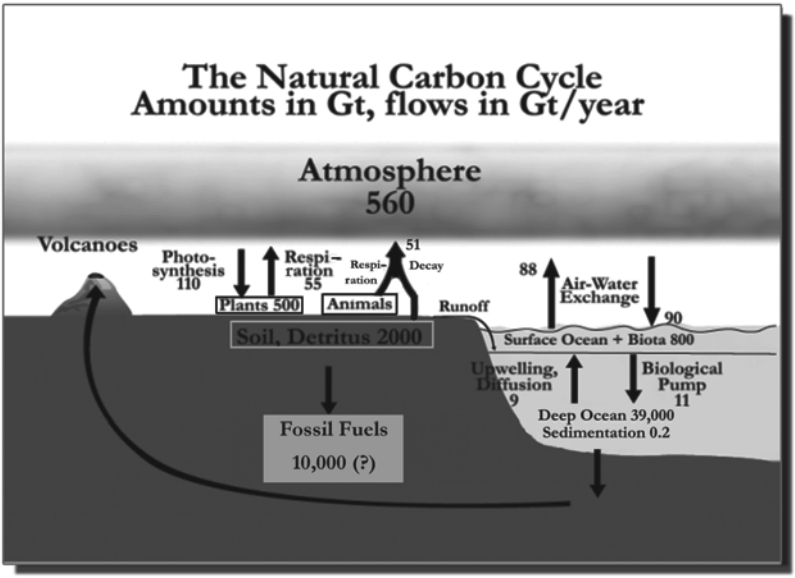


Figure 9

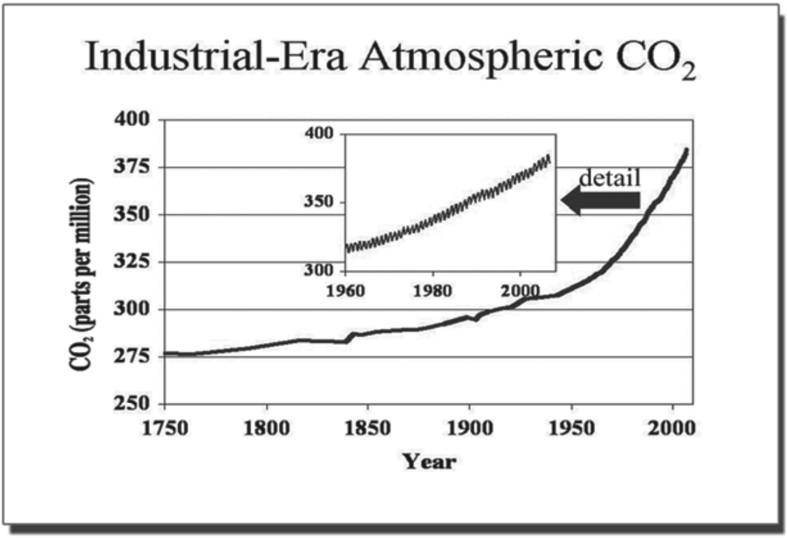


Figure 10 Detail shows the very accurate CO_2 measurements made since the 1950s.

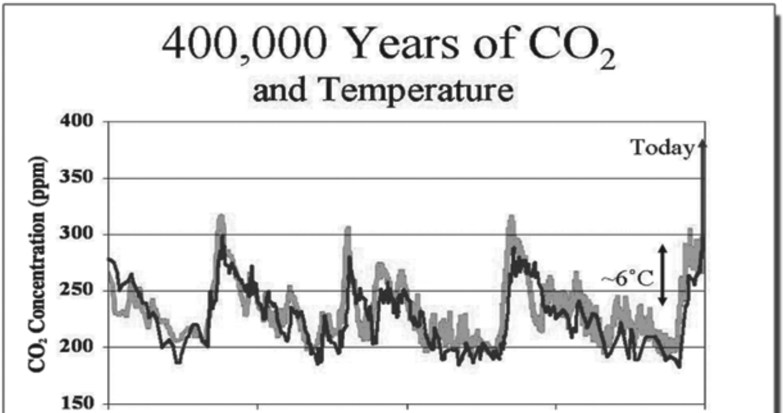
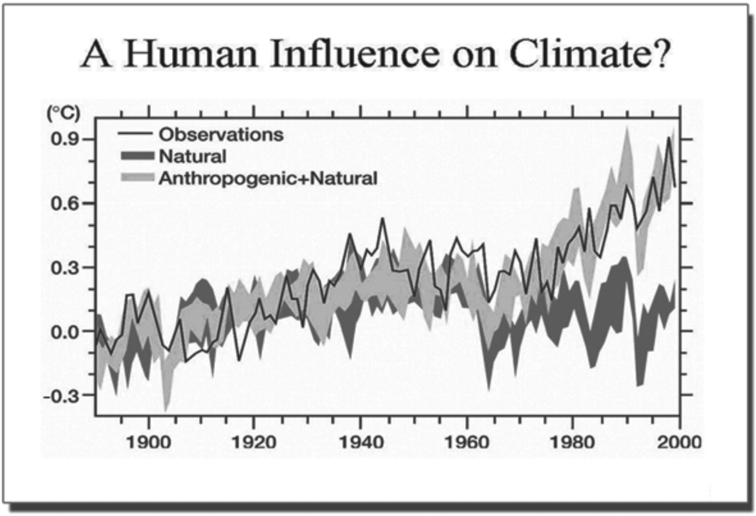
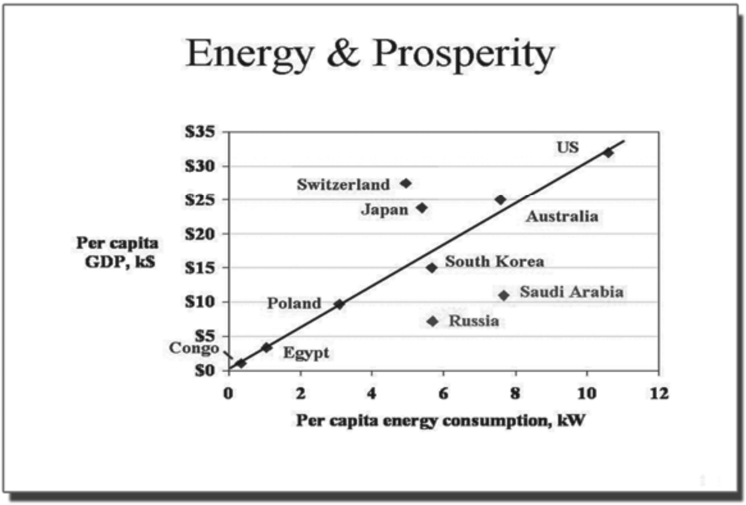


Figure 11



A Human Influence on Climate?

Figure 12



Energy & Prosperity

Figure 13

Mt. Pinatubo Eruption
A Natural Climate Experiment

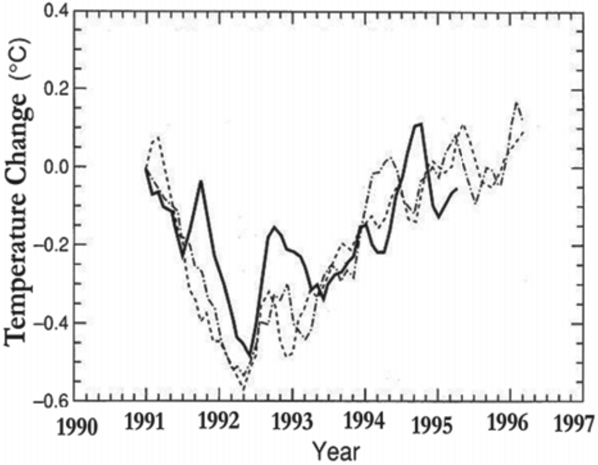
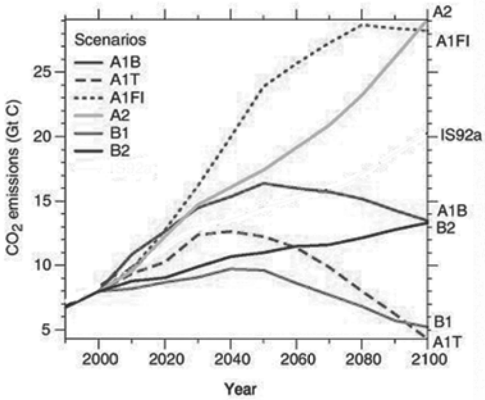
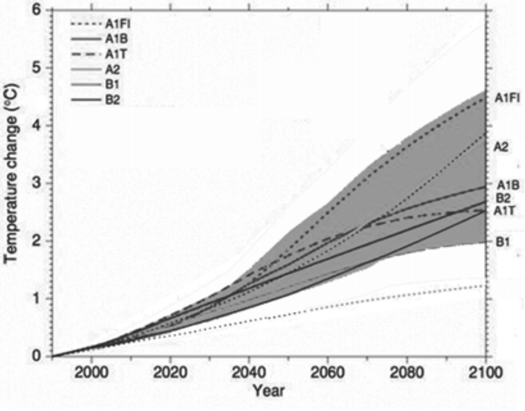


Figure 14

CO$_2$ and Temperature Projections

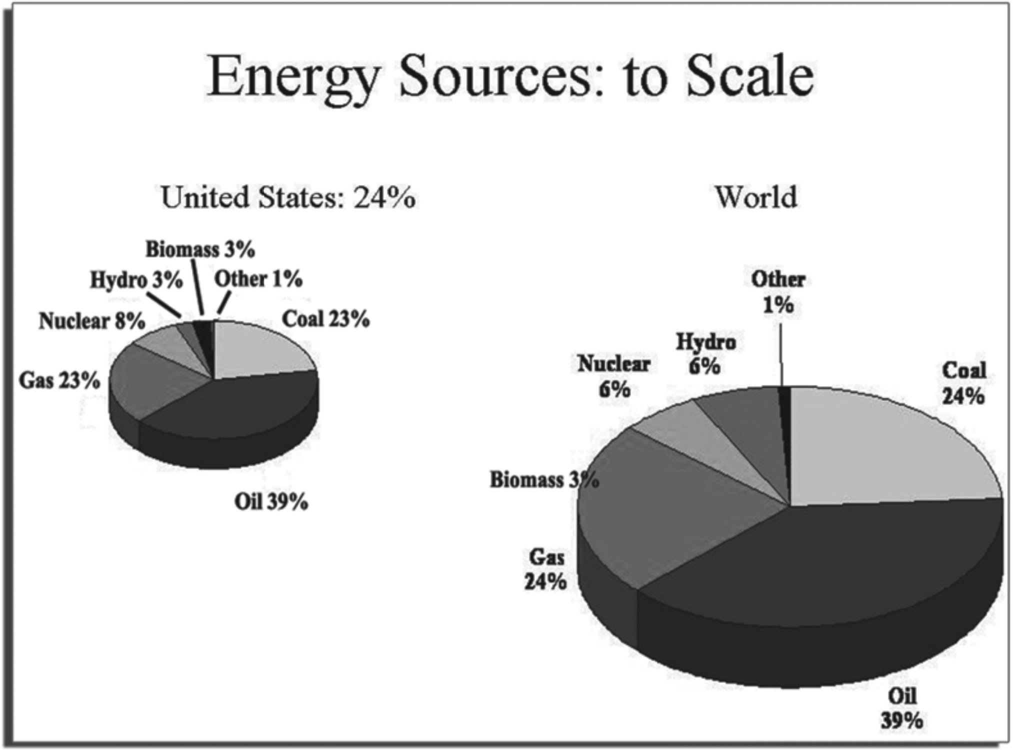


CO$_2$ emissions



Global temperature

Figure 15



Energy Sources: to Scale

United States: 24%

World

Figure 16

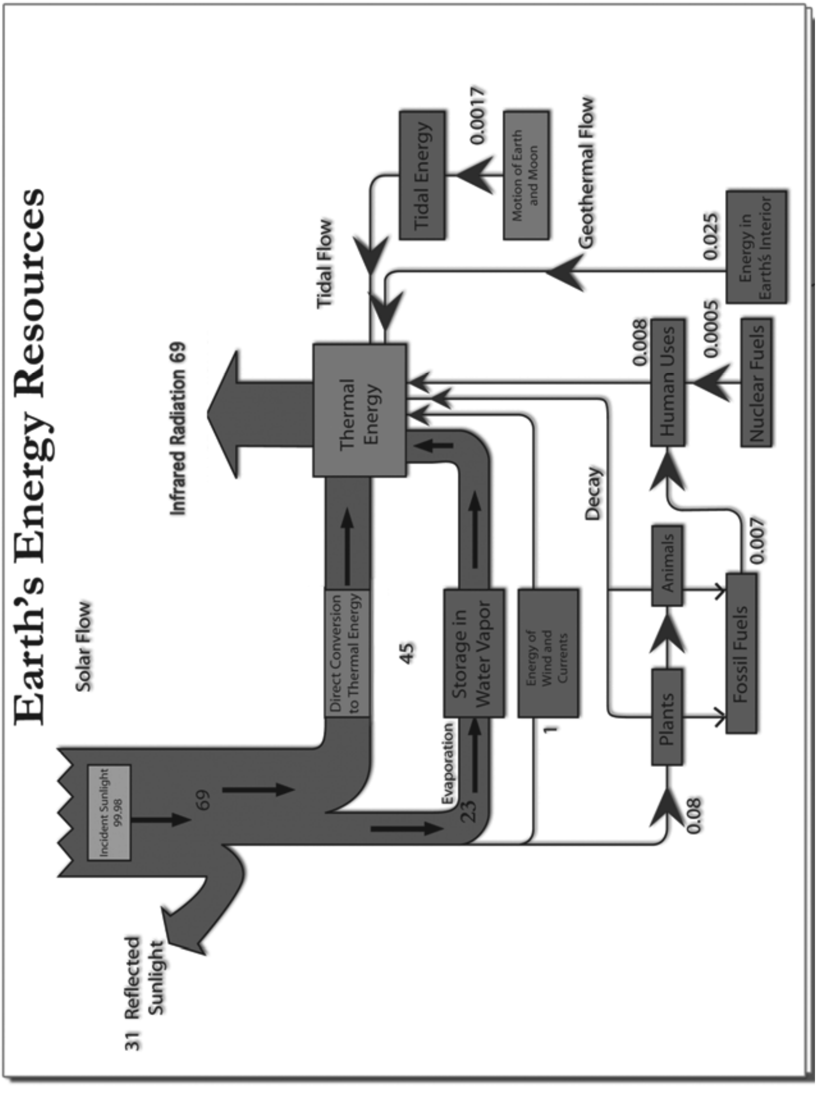

Earth's Energy Resources
Solar Flow
Infrared Radiation 69
Tidal Flow
0.0017
Tidal Energy
Motion of Earth and Moon
Geothermal Flow
Incident Sunlight 99.98
69
Direct Conversion to Thermal Energy
45
Thermal Energy
0.025
Energy in Earth's Interior
31 Reflected Sunlight
Evaporation
23
Storage in Water Vapor
Energy of Wind and Currents
1
Decay
0.008
0.0005
Human Uses
Nuclear Fuels
0.08
Plants
Animals
Fossil Fuels
0.007

Figure 17

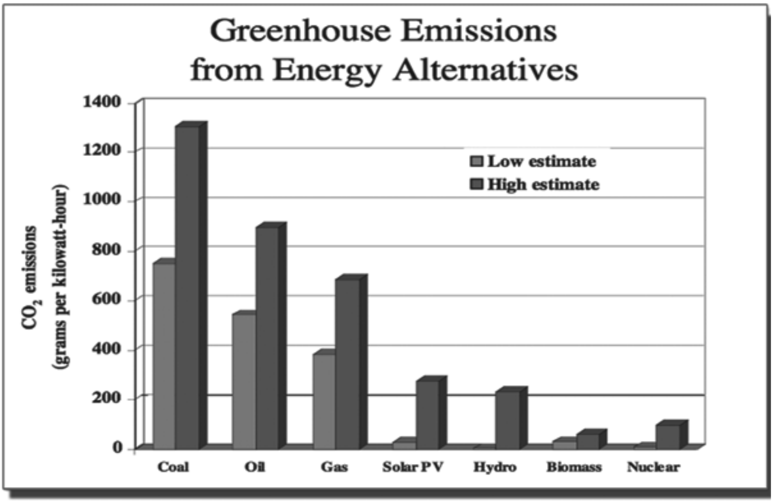


Figure 18

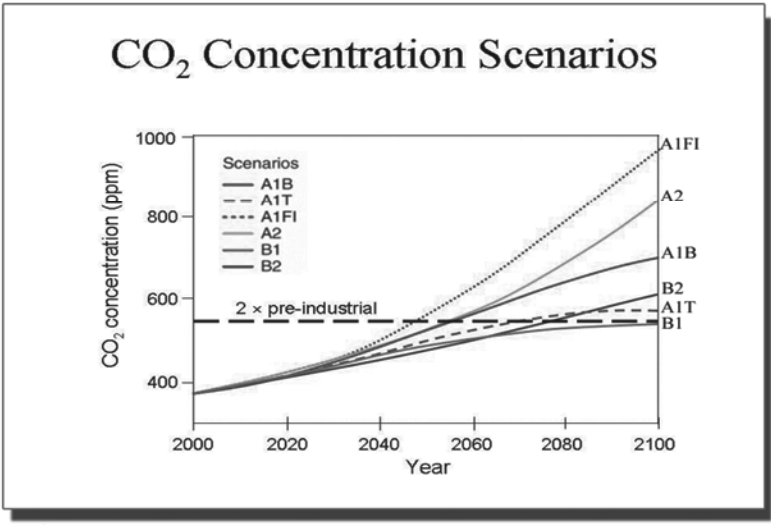
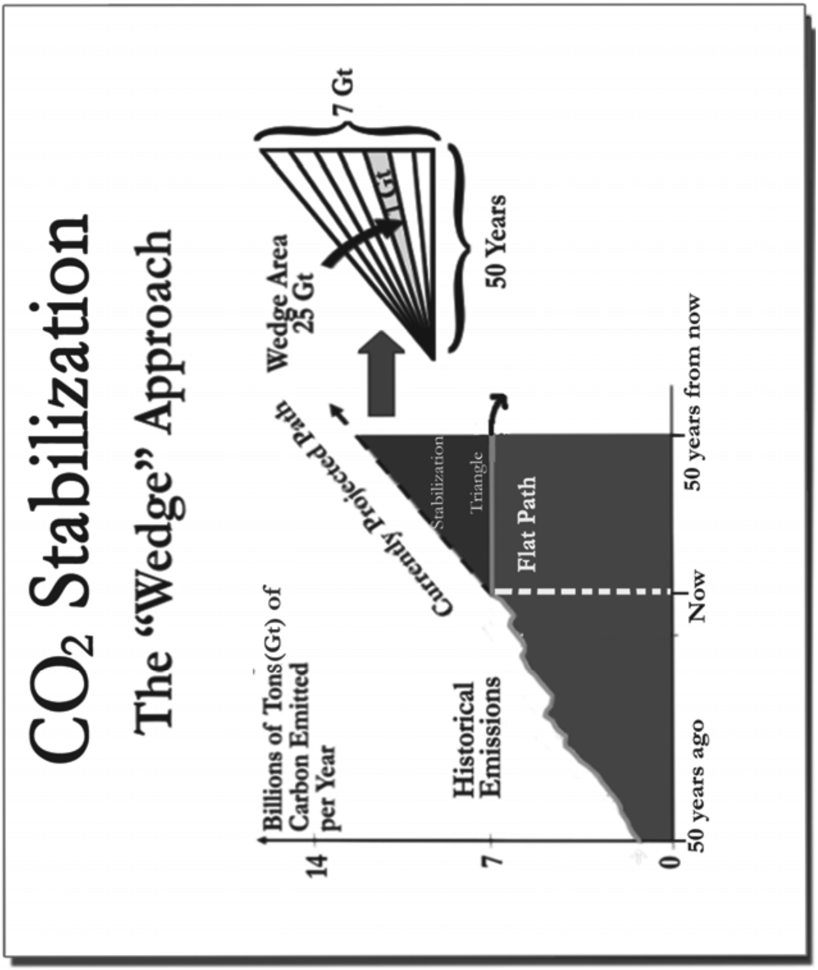


Figure 19



CO_2 Stabilization

The "Wedge" Approach

Figure 20

Data Sources for Figures

Figure 1: © Crown copyright 2007, data supplied by the Met Office Hadley Centre and CRU.

Brohan, P., J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones. 2006. Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J. Geophys. Res*. 111, D12106, doi:10.1029/2005JD006548.

Figure 2: National Snow and Ice Data Center.

Figure 3: The Teaching Company. Data provided by Kerry A. Emanuel: http://wind.mit.edu/~emanuel/Papers_data_graphics.htm.

Figure 4: Robert A. Rohde / Global Warming Art.

Figures 5, 6, 8, 11: Jouzel, J., C. Lorius, J. R. Petit, C. Genthon, N. I. Barkov, V. M. Kotlyakov, and V. M. Petrov. 1987. Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). *Nature* 329: 403-8.

Jouzel, J., N. I. Barkov, J. M. Barnola, M. Bender, J. Chappellaz, C. Genthon, V. M. Kotlyakov, V. Lipenkov, C. Lorius, J. R. Petit, D. Raynaud, G. Raisbeck, C. Ritz, T. Sowers, M. Stievenard, F. Yiou, and P. Yiou. 1993. Extending the Vostok ice-core record of palaeoclimate to the penultimate glacial period. *Nature* 364: 407-12.

Figure 7: Kiehl, J. T., and K. E. Trenberth. 1997. Earth's annual global mean energy budget. *Bulletin of the American Meteorological Society* 78: 206, figure 7.

Figure 9: The Teaching Company. Adapted with permission from Wolfson, R., 2007, *Energy, Environment, and Climate* (W.W. Norton & Co.).

Figure 10: Neftel, A., H. Friedli, E. Moor, H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer. 1994. Historical CO_2 record from the Siple Station ice core. In *Trends: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Etheridge, D. M., L. P. Steele, R. L. Langenfelds, R. J. Francey, J.-M. Barnola, and V. I. Morgan. 1998. Historical CO_2 records from the Law Dome DE08, DE08-2, and DSS ice cores. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak

Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Keeling, C. D., and T. P. Whorf. 2005. Atmospheric CO_2 records from sites in the SIO air sampling network. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Figure 12: Parallel Climate Model/DOE/UCAR.

Meehl, G. A., W. M. Washington, C. M. Ammann, J. M. Arblaster, T. M. L. Wigley, and C. Tebaldi. 2004. Combinations of Natural and Anthropogenic Forcings in Twentieth-Century Climate. *Journal of Climate* 17: 3723, figure 2(d).

Figure 13: The Teaching Company. Data selected from Key World Energy Statistics 2006 © OECD/IEA, 2006, pp. 48-57.

Figure 14: Intergovernmental Panel on Climate Change

IPCC, 1996: *Climate Change 1995: The Science of Climate Change*, p. 258.

Figure 15: Intergovernmental Panel on Climate Change

IPCC, 2001: *Climate Change 2001: The Scientific Basis*, p. 64.

Figure 16: Energy Information Administration

EIA, Annual Energy Review 2004, Table 1.3

EIA, International Energy Annual 2003, Table 1.8.

Figure 17: The Teaching Company. Adapted with permission from Wolfson, R., 2007, *Energy, Environment, and Climate* (W.W. Norton & Co.), and Romer, Robert H, 1985, *Energy Facts & Figures* (Spring Street Press, Amherst, MA). Romer is the original source for the figure.

Figure 18: The Teaching Company. Data from International Atomic Energy Agency, excepting the nuclear high value. Spadaro, J. V., L. Langlois, and B. Hamilton. 2000. Greenhouse Gas Emissions of Different Electricity Generating Chains, *IAEA Bulletin* 42 (2). Nuclear high value is an estimate based on a survey of the literature.

Figure 19: Intergovernmental Panel on Climate Change

IPCC, 2001: *Climate Change 2001: The Scientific Basis*, p. 222.

Figure 20: The Teaching Company. Sources:

Marland, G., T. A. Boden, and R. J. Andres. 2006. Global, Regional, and National CO_2 Emissions. In *Trends: A Compendium of Data on Global*

Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Socolow, R. 2005. Stabilization Wedges: Mitigation Tools for the Next Half-Century. Presentation at Avoiding Dangerous Climate Change: A Scientific Symposium on Stabilisation of Greenhouse Gases. February 3, 2005. Met Office, Exeter, UK. The presentation was based on Pacala, S., and R. Socolow, 2004, Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, *Science* 305: 968-972.

Glossary

active solar: Technologies that use mechanical or electrical components to facilitate energy collection and storage.

aerosols: Particulate matter suspended in the atmosphere.

albedo: The reflectivity of a surface or material, expressed as a number between 0 and 1 that gives the fraction of incident light that is reflected.

anthropogenic: Of human origin.

biological pump: The process whereby dead marine organisms and their waste products sink into the deep ocean, taking carbon with them.

carbon capture and sequestration: The process of capturing carbon dioxide either before or after combustion and storing it where it cannot get into the atmosphere.

carbon cycle: The cycling of carbon through the atmosphere, biosphere, oceans, and Earth’s crust.

CCS: See **carbon capture and sequestration**.

cell: The smallest division of Earth’s surface, atmosphere, or ocean in a climate model.

climate: The long-term average patterns of temperature, precipitation, humidity, and other weather-related quantities.

climate model: A mathematical representation of the climate system, usually implemented in a computer program; used to study climate processes and to explore projections of future climate.

coupled model: A climate model that couples together two or more separate models, typically of the surface/atmosphere and, separately, the oceans.

cryosphere: Earth’s frozen sector, comprising the polar ice caps, floating sea ice, and glaciers.

diurnal temperature range: The typical variation in temperature from night to day at a given location.

energy balance: The condition in which a system loses as much energy as it gains, thus maintaining a constant temperature.

energy intensity: A measure of the energy required to produce a given unit of gross domestic product.

enhanced greenhouse effect: The trapping of additional infrared, with subsequent warming of Earth's surface, by greenhouse gases of anthropogenic origin.

equilibrium: A state of balance in which nothing changes.

feedback effect: A change in a system that occurs as a result of another change, either enhancing (positive feedback) or diminishing (negative feedback) the original change.

fission: The splitting of heavy nuclei to release energy.

flow: A stream of energy, such as sunlight coming to Earth.

fossil fuels: The fuels coal, oil, and natural gas, formed over millions of years from organic material trapped underground before it has a chance to decay fully. The energy contained in fossil fuels originated in sunlight and was captured through photosynthesis.

fuel: A material substance that stores energy.

fusion: The joining of light nuclei to release energy.

GCM: Global climate model or global circulation model.

gigatonne: One billion tonnes, a unit useful in describing global carbon flows.

greenhouse effect: Warming of a planet's surface caused by the absorption and re-radiating of outgoing infrared radiation by gases, clouds, or aerosols.

greenhouse gas: A gas that absorbs infrared radiation, thus contributing to the greenhouse effect.

hydrologic cycle: See **water cycle**.

ice age: A long period of cool climate, characterized by mile-thick ice sheets covering the polar regions and extending, in the northern hemisphere, into what is now the northern United States.

indirect aerosol effect: A secondary effect whereby aerosols act as cloud condensation nuclei, with the resulting clouds then reflecting sunlight to produce a cooling effect.

indirect solar: Energy technologies based on wind, water, or biomass. The ultimate source of their energy is sunlight, but they do not use sunlight directly.

interglacials: Relatively brief periods of warmer conditions occurring between the much longer ice ages.

isotopes: Versions of the same element that differ in the number of neutrons in their nuclei and, thus, in mass. Subtle changes in the concentration of different isotopes provide proxies for temperature and other quantities in the distant past.

latent heat: Energy stored by virtue of a substance's being in a gaseous or liquid phase. The energy can be released as sensible heat when the gas condenses to liquid or the liquid solidifies.

MAT: Marine air temperature.

metric ton: 1000 kilograms, or 1.1 U.S. tons. Also, tonne (t).

model validation: Any procedure used to demonstrate that a climate model correctly reproduces climatic conditions.

Moore's law: The exponential increase in computing power that has computer speeds doubling roughly every 18 months.

natural greenhouse effect: The natural warming of Earth's surface through the greenhouse effect resulting from naturally occurring water vapor and carbon dioxide. The natural greenhouse effect keeps Earth's surface 33°C (about 60°F) warmer than it would otherwise be.

negative feedback: A feedback effect that diminishes the original change.

nuclear fuel: A fuel whose energy is stored in its atomic nuclei.

passive solar: Technologies that harness solar energy without moving parts, such as pumps, fans, and the like.

photosynthesis: The process whereby green plants take in carbon dioxide and sunlight to manufacture sugars, which store energy that ultimately comes from the Sun.

photovoltaic cells: Devices that convert sunlight directly into electricity.

positive feedback: A feedback effect that enhances the original change.

power: The rate of energy use or production.

proxy: A measurable quantity whose value helps determine the value of a quantity that can't be measured directly—as in the use of tree-ring data to calculate temperatures when thermometric records aren't available.

reservoir: A system that acts as temporary or long-term storage for materials cycling in the Earth system. Living things, for example, constitute a reservoir for carbon.

resolution: The fineness of the scale into which a climate model divides Earth's surface, atmosphere, and ocean. Higher resolution means a finer scale.

respiration: The opposite of photosynthesis; living things take in oxygen, which reacts with food to release energy and carbon dioxide.

SAT: Surface air temperature.

SST: Sea-surface temperature.

stratosphere: An atmospheric layer extending from the top of the troposphere to about 50 kilometers, in which most solar ultraviolet radiation is absorbed.

sub-grid parameterization: A procedure used to represent phenomena, such as the structure of clouds, that are smaller than the cell size of a climate model.

sulfate aerosols: Aerosol particles formed from sulfate (SO_4) compounds. Sulfate aerosols are highly reflective and, thus, produce a cooling effect.

thermohaline circulation: Oceanic circulation driven by a combination of temperature and salinity differences.

tonne: See **metric ton**.

troposphere: The lower level of the atmosphere, extending to about 8 to 18 kilometers, in which nearly all weather phenomena occur.

urban heat island effect: An apparent warming due to the growth of cities, which are warmer than their rural surroundings.

water cycle: The cycling of water through the Earth system, by evaporation, precipitation, and the flow of rivers and groundwater.

watt: A unit of power—the rate of energy use or production; 1 watt is 1 joule per second and is about 1/100 of the power output of a typical human body.

weather: The particular conditions that describe the state of the atmosphere in a given location and at a given time.

Bibliography

Readings:

Glantz, Michael. *Climate Affairs: A Primer*. Washington, DC: Island Press, 2003. A general-audience discussion of climate change and its impacts by a social scientist who is the former head of the Environmental and Societal Impacts Group at the National Center for Atmospheric Research.

Harvey, L. D. D. *Global Warming: The Hard Science*. Essex, England: Prentice Hall, 2000. A thorough exploration of the science behind global climate change. Doesn't spare the math but relegates the most complex math to boxes that the reader is free to skip.

Houghton, John. *Global Warming: The Complete Briefing*, 3rd ed. Cambridge: Cambridge University Press, 2004. A thoroughly readable, up-to-date account of climate change by a former chair of the Scientific Assessment Working Group of the Intergovernmental Panel on Climate Change.

Intergovernmental Panel on Climate Change. *Carbon Capture and Storage* (IPCC 2005). Cambridge: Cambridge University Press, 2005. A detailed report suggesting that CCS could play a significant short-term role in mitigating the effects of fossil-fuel combustion on climate. Also available at http://www.ipcc.ch.

———. *Climate Change 2001: The Scientific Basis* (IPCC 3). Cambridge: Cambridge University Press, 2001. This is the science portion of the IPCC's third assessment report—a comprehensive survey of the state of climate science at the turn of the 21st century. Superceded by IPCC 4 but still full of useful background information. Also available at http://www.ipcc.ch.

———. *Climate Change 2007: The Physical Science Basis* (IPCC 4). Cambridge: Cambridge University Press, 2007. This is the science portion of the IPCC's fourth assessment report—a comprehensive survey of the state of climate science in the early 21st century. Also available at http://www.ipcc.ch.

Lovins, Amory B., E. K. Datta, O-E Bustnes, J. G. Koomey, and N. J. Glasgow. *Winning the Oil Endgame: Innovation for Profits, Jobs, and Security*. Snowmass, CO: Rocky Mountain Institute, 2005. A quantitative and elaborately documented report showing how humanity might end its dependence on climate-changing fossil fuels. Also available in full at http://www.oilendgame.com.

Pacala, Stephen, and Robert Socolow. “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies.” *Science* 305 (13 August 2004), pp. 968–972. A visionary paper that shows how we might break the seemingly insurmountable climate problem into manageable pieces.

Parmesan, Camille, and Gary Yohe. “A Globally Coherent Fingerprint of Climate Change Impacts Across Natural Systems.” *Nature* 421 (2 January 2003), pp. 37–42. This paper presents a “metastudy” of hundreds of different research results that point to climate-change impacts on species ranges.

Ruddiman, William. *Earth’s Climate: Past and Future*. New York: W.H. Freeman, 2001. An authoritative and beautifully illustrated textbook on climate, with emphasis on paleoclimate.

Schneider, Stephen, Armin Rosencranz, and John O. Niles, eds. *Climate Change Policy: A Survey.* Washington, DC: Island Press, 2002. This is a collection of essays dealing mostly with policy issues related to climate change. But the first chapter is a concise introduction to the science of climate change.

Smil, Vaclav. *Energy: A Beginner’s Guide*. Oxford, England: Oneworld Publications, 2006. A quick guide to energy by a leading specialist and prolific writer on energy issues. Particularly strong on energy history.

———. *Energy at the Crossroads: Global Perspectives and Uncertainty*. Cambridge, MA: MIT Press, 2003. A thorough, scholarly, but eminently readable account of energy history, alternatives, and possible energy futures from a truly independent thinker on the subject.

Stern, Nicholas. *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press, 2006. A thorough review of the potential economic impacts of climate change by a leading British economist and former chief economist at the World Bank.

Stott, Peter A., Dáithí A. Stone, and Myles R. Allen. “Human contribution to the European heatwave of 2003.” *Nature* 432 (December 2, 2004), pp. 610-614. This paper makes a statistical argument that the European heat wave of 2003 is unlikely to have resulted from natural factors alone, but that anthropogenic greenhouse warming likely contributed to the event.

Weart, Spencer. *The Discovery of Global Warming*. Cambridge, MA: Harvard University Press, 2003. A history of global warming from the 19th century onward, tracing how the idea of anthropogenic warming first dawned on scientists, then spread into the broader society.

Wolfson, Richard. *Energy, Environment, and Climate*. New York: W.W. Norton, 2007. A textbook intended for mid-level undergraduate courses that explores the science of, and connections between, energy and climate. Some math but no calculus.

Internet Resources:

British Treasury Department. From this site, you can download all or part of the 700-page Stern Review on the Economics of Climate Change. http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm.

Carbon Dioxide Information Analysis Center. This Web site offers a host of data and graphics on global temperatures, greenhouse gases, and other climate-related parameters. Here, you can also find graphs and data on global and regional temperatures and atmospheric carbon dioxide from sites around the world on time scales ranging from decades to hundreds of thousands of years. http://cdiac.ornl.gov/.

Climate Prediction Experiment. Participate in a worldwide climate modeling experiment! ClimatePrediction.net harnesses the spare computing power of personal computers worldwide to run multiple simulation experiments using the world's most sophisticated climate models. You can sign your own computer up to participate and keep yourself posted on the results of the ClimatePrediction experiments. http://www.climateprediction.net.

Climatic Research Unit, University of East Anglia. Probably the most authoritative source for the instrumental temperature record discussed in Lecture One. http://www.cru.uea.ac.uk/.

Hadley Centre of the British Meteorological Office. The highly respected British Met (for Meteorological) Office provides a thorough introduction to the greenhouse effect and a thorough discussion of the carbon cycle through its Hadley Centre for Climate Change. http://www.metoffice.gov.uk.

Intelligent Energy Europe. This European Commission site features myriad links to programs and information related to the European Union's vigorous pursuit of non-fossil energy. http://ec.europa.eu/energy/index_en.html.

Intergovernmental Panel on Climate Change. This site features links to the latest IPCC Assessment Report, as well as many additional reports on more specialized climate topics. http://www.ipcc.ch.

International Energy Agency (IEA). This site lets you generate energy data for your choice of country, region, and energy type from the IEA's vast database. A click on the Key Statistics link gets you to a free download of the annual *Key World Energy Statistics*.
http://www.iea.org/Textbase/stats/index.asp.

National Renewable Energy Laboratory. At this U.S. Department of Energy site, you can find out about research into alternative energy technologies. http://www.nrel.gov/.

National Snow and Ice Data Center. Images and data showing changing conditions in Earth's cryosphere. http://nsidc.org/.

Pew Center on Global Climate Change. Covers all aspects of climate change and is especially strong on helping the business community find solutions to greenhouse emissions. On the "Global Warming in Depth" page (http://www.pewclimate.org/global-warming-in-depth), the Economics and Environmental Impacts links carry more detailed information relevant to Lecture Nine. http://www.pewclimate.org/.

Princeton Environmental Institute Carbon Mitigation Initiative. This Princeton University site provides a detailed description of the "wedge" approach to greenhouse stabilization, including a movie, a simulation game, and links to the original papers.
http://www.princeton.edu/~cmi/resources/stabwedge.htm.

RealClimate. This blog, maintained by scientists active in climate research, has technically accurate, detailed discussions of climate issues and, particularly, the attribution of climate change to human activities. Search the site on "attribution" for discussions relevant to Lecture Seven. http://www.realclimate.org.

U.S. Department of Energy, Energy Information Administration, *Annual Energy Review*. Published yearly and made available on the Web, the *Annual Energy Review* is a comprehensive compilation of energy statistics for the United States. There's a less detailed section entitled "International Energy." Most of the data are displayed in both tables and graphs, and the tables are available for download as spreadsheets.
http://www.eia.doe.gov/emeu/aer/.

U.S. Department of Energy, Energy Information Administration, *International Energy Annual*. A more comprehensive compilation of international energy statistics. http://www.eia.doe.gov/iea/.

U.S. Environmental Protection Agency (EPA), “Greenhouse Gas Emissions.” This EPA site is an authoritative source for detailed statistics on U.S. greenhouse gas emissions. http://www.epa.gov/climatechange/emissions/index.html.

World Glacier Monitoring Service. This Swiss site carries yearly data on hundreds of glaciers worldwide. http://www.geo.unizh.ch/wgms/.